Date of Publication:
30/07/2012

Cunninghamia
A journal of plant ecology for eastern Australia

The Royal
Botanic Gardens
& Domain Trust

ISSN 0727-9620 (print) • ISSN 2200-405X (Online)

## SHORT COMMUNICATION

# Using Australian Virtual Herbarium data to find all the woody rain forest plants in Australia

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***Abstract***: Data bases that provide continental and global scale information about species distributions provide a valuable resource for environmental, ecological and evolutionary research. However to bring a large dataset to a standard that is suitable for quantitative analysis, data quality needed to be checked. Here we provide a worked example using a large dataset (c. 320,000 records) from Australia's Virtual Herbarium (AVH) database, based on an initial data request for full distribution data for c. 2600 woody rain forest species known to occur in Australia. To reconcile inconsistencies around taxonomic identity prior to merging with our trait data-base, and resolve issues around spatial resolution and accuracy, we implemented extensive data filtering using a 'cloud-based' solution (Google Refine). This systematic process resulted in 1) the removal of close to 45% of the records originally downloaded, and 2) a clean and powerful data set based on herbarium backed distribution records for Australia's woody rain forest species. Such resources can contribute significantly to improving research outcomes related to understanding Australia's vegetation.

Key words: Australian Virtual Herbarium, Atlas of Living Australia, databases, data cleaning, rain forest woody plants, species distributions

***Cunninghamia* (2012) 12(3): 177-180**
doi: 10.7551/cunninghamia.2012.12.014

## Introduction

Collections record databases such as Australia's Virtual Herbarium (AVH: www.chah.gov.au/avh) and the Australian Faunal Directory (AFD) delivered through the Atlas of Living Australia (ALA) (www.ala.org.au) provide a valuable resource describing the spatial distribution of Australian flora and fauna species. These sorts of data are increasingly used in environmental, ecological and evolutionary research, for example, 1) as part of global biodiversity informatics compilations, 2) to examine the spatial distribution of species in relation to climate change susceptibility (Gallagher et al. 2009), 3) to examine the distribution of species across geographic space and environmental gradients (Crisp et al. 2001; Mellick et al. 2011), and 4) in relation to quantified measures of evolutionary signals from phylogeny, taxonomy, endemism and genetic diversity (Bickford et al. 2004; Laffan & Crisp 2003; Rosauer et al. 2009).

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The purpose of this short note is to highlight some of the data quality issues that might need to be dealt with in order to bring these large datasets to a standard that is suitable for quantitative ecological research. The spatial distribution issues of these data are well documented (e.g. Chapman 1998; Crisp et al. 2001; Newbold 2010), but there remain other issues of database accuracy, from factors such as taxonomic revisions, and data entry errors and ambiguities. A strategy for cleaning a data set of these issues is rarely examined in detail. Here we list the general issues and major problems relating to such datasets, and illustrate how we systematically addressed them in an example from our own research. Our research questions required location and distribution data for all Australian woody rain forest species (trees, shrubs and vines). These data needed to be reconciled with a trait data base and a background tree (phylogenetic) for detailed evolutionary-ecology analyses using updated information from the Angiosperm Phylogeny Group III website (APGIII, http://www.mobot.org/mobot/research/apweb/). While the data base (which contains c. 6 M collection records) is available to the public, some limitations are in place related to accessing full location data. Consequently full access to the dataset was obtained through the National Herbarium of NSW.

### *Methods and progressive outcomes of data cleaning*

Our research required the compilation of distributional records (latitude and longitude) for c. 2600 woody Australian rain forest plant taxa (trees, shrubs and vines). This compilation was intended to cover the full distribution of rain forest on the Australian continent and the whole eastern sea-board from Tasmania to Cape York, and westward to the Northern Territory and the Kimberley region. Records for some taxa extended into drier non-rain forest areas of the continent.

The downloaded data set contained a range of inconsistencies across various fields that complicated the automation of follow-up analyses. For example: 1) collection locations by states given in full and abbreviated form, with and without capitalization (NT, Northern Territory, northern territory), and missing entirely (nulls); 2) plant names and authorities in multiple forms, both within a species and between species; 3) 'subspecies' and 'variety' abbreviated in different ways (e.g. subsp. and ssp.); 4) multiple acronyms for each institution; 5) null values for many geographical coordinates; 6) inconsistent geocode precision, with numerous nulls; 7) collection dates given in different formats; and 8) replications of the same collection(s). A range of issues emerged:-

### *Taxonomic precision, reconciling names (part I)*

A total of c. 320 000 records were initially downloaded for the c. 2600 name queries. These data were loaded into Google Refine (www.google.com/p/google-refine/) as a comma separated variable (csv) file. We used a text facet feature to identify and group all taxa. At this stage the c. 2600 species were represented by 6742 names. A text clustering algorithm was then used to group names by (text) similarity. This process identified 672 clusters that represented names with close equivalents such as subspecies, variety, or the same name with different taxonomic authorities. As a first step these were reconciled and merged, where appropriate. The clustering process resulted in the retention of c. 210 names from the 672 clusters, leaving 6280 names.

### *Taxonomic precision, updating taxonomy (part II)*

Most studies will need a systematic process of reconciling and updating species names to an accepted standard. Here we used APGIII and a process of reconciling with the underlying phylogenetic file of all Australian rain forest taxa we had previously created for this purpose (Kooyman personal data). This involved working through the remaining 6280 names in the data set one at a time using the text facet function (in Google Refine). Where appropriate, identities were merged, allocated to subspecies or variety consistent with the literature, or, very occasionally, deleted where infra-

**Table 1 Steps undertaken in cleaning data downloaded from Australia's Virtual Herbarium data base. Initial data request was for full distribution data for c. 2600 woody rain forest species known to occur in Australia.**

| **STEPS** | **Records (c. number)** | **Species ID's (c. number)** |
|---|---|---|
| initial download | 320000 | 6742 |
| *Taxonomic precision (part 1)* | | |
| first filter (clustering) | 320000 | 6280 |
| *Taxonomic precision (part 2)* | | |
| filtering by species | 320000 | 2600 |
| conspecific merge | 320000 | 2560 |
| *Defining and delimiting the data set* | | |
| remove marginal taxa | 280000 | 2360 |
| final taxonomic clean | 270000 | 2300 |
| *Data quality and precision, geocode precision* | | |
| geocode precision | 260000 | 2300 |
| duplications (distribution records) | 230000 | 2300 |
| *Data quality and precision, cultivated material* | | |
| cultivated specimens | 220000 | 2300 |
| *Data quality and precision, latitude and longitude* | | |
| spatial filtering (coordinates) | 200000 | 2300 |
| *Final spatial filtering and corrections* | | |
| spatial filtering (map and coordinates) | 180000 | 2300 |

specific species could not be reconciled with extant taxa. This reduced the number of names to c. 2600 which were then checked against the base phylogenetic file that included all of Australia's woody rain forest plant species. At this stage we identified 17 taxa missing from the original data request due to spelling errors or different spellings in our original search. These were corrected and the data was downloaded and merged with the partly cleaned data, resulting in all species being present in the data set. At this point we identified a number of 'unnamed species' conspecific with other 'species' in the data. Merging these reduced the final number of species by c. 40 taxa.

### *Defining and delimiting the dataset*

The focus of this study was on woody obligate rain forest species. We deliberately excluded mangroves, wet and dry sclerophyll species, herbs, and some desert taxa that occur close to monsoon vine forests in the tropics. This filtering process resulted in the removal of c. 200 species (in total) from those originally requested. Palms, ferns and cordylines were not included in the original data request because trait compilations were focused on woody taxa that had comparable and equivalent traits (refer to Kooyman et al., 2010, 2011, 2012).

### *Data quality and precision, geocode precision*

Spatial resolution is an issue for all studies, and choices around what level of geocode precision to retain will be influenced by a range of factors, including, for example, the desirability of retaining older collection records for comparison. We allocated the AVH measures of geocode precision to ranked values. All records with geocode precision >25 000 metres were removed, resulting in c.10 000 records including most of the 'older' records being deleted. A secondary filtering process based on an assessment of geocode precision relative to other location records for the same taxon was then undertaken to test if locations with differing precisions were closely aligned (or widely divergent) for the same locations (described in the text location descriptions). Records that aligned consistently were retained. Records that did not were removed. In addition, whenever duplicate records were encountered they were removed. This resulted in c. 23 000 records (total) being removed.

### *Data quality and precision, cultivated material*

The focus then shifted onto removing records of all non-wild-collected (cultivated) specimens. Cultivated specimens were defined as those recorded as having been collected from public and private botanic gardens, arboreta, and research and experimental plantings. Filtering searches required every name variation for each agency, individual, and herbarium to be identified and used (with case sensitivity removed) to identify all cultivated specimens. These were all removed, resulting in another large (c. 10 000) reduction in numbers.

### *Data quality and precision, latitude and longitude*

Spatial distribution accuracy is a key component of data reliability for analyses. We began by filtering the data by species locations (latitude and longitude). Latitude and longitude fields (columns) were first duplicated and rounded down to the nearest degree (no decimal places). This allowed for another round of facet filtering by species and locations for each taxon. The known distributional extent of species (Kooyman personal data) was used to check if the AVH records fell within the broad parameters of species known distributions. The process of checking (though still reliant on prior knowledge) can also be performed in the Biodiverse software package (Laffan et al. 2010). The filtering process highlighted numerous records with incorrect coordinates (including records seaward of the coast and not corresponding to known islands with rainforest), and incorrect data entry. These were removed for all taxa one at a time, resulting in many 1000s of deletions. An alternative to this process would be a record by record comparison of geocodes (Lat. Long.) to described collection locations, followed by manual correction of latitude and longitude errors. While considerably more laborious, this process could result in the retention of many more records, but time constraints did not permit this option in this case.

Following that filtering process, the spatial mapping facet was activated (in Google Refine) using the actual coordinates. This allowed all remaining species records seaward of the coast, and other anomalous records to be highlighted. Those not occurring on islands, or on distant oceanic islands, were removed. A species by species reconciliation of known spatial distribution with the AVH data distribution records was then undertaken for all taxa in the list. This process also detected the residue of cultivated arboretum and collection (planting) records remaining in the data, and the remaining errors (incorrect data entries, poor location information and other factors). All these were removed.

### *Final filtering*

At this point c. 45% of the records originally downloaded for the research project had been removed for various reasons in the data cleaning and filtering process. Several of the filtering processes were then repeated (including text facet filtering, location coordinate filtering, and location description filtering) to detect any residue of error using text identification commands with variations of key words previously found to provide the main errors. Other command lines (e.g. planted, 'name of towns', street, island) were then tested to detect any other logical errors. As a final filter the whole process of spatial reconciliation for each species (c. 2300) was repeated and double checked. This resulted in the removal of a small but significant number of errors (e.g. inland and desert locations for coastal species) that would create noise in any subsequent spatial analyses.

The outcomes of the filtering processes described are listed in Table 1. Following the final filtering the data could be described as taxonomically and spatially clean, with high accuracy relative to available data on species distributions.

## Discussion

For such a large dataset, many weeks were needed to complete data filtering, and the final outcome was made possible by a close working knowledge of the flora and the individual taxa. The objectives of other researchers relative to different projects may vary significantly, as will the time required to undertake the filtering and cleaning. However, the general process and sequence of steps in filtering and cleaning the data using the tools suggested will remain similar, but may vary relative to research objectives. The limitations of herbaria and museum data in relation to capturing complete species distributions was described by Newbold (2010) who advocated supplementing those data with distribution modelling. Depending on the scales and resolution required for any particular study question, this remains an option (e.g. Crisp et al. 2001; Mellick et al. 2011).

Alternative processes for some aspects of the data cleaning and reconciliation include bringing species binomials to a common taxonomy across datasets by matching names against the accepted names in the Plant List (www.theplantlist.org/) and / or sources such as the International Plant Name Index (IPNI; www.ipni.org/) and Tropicos (www.tropicos.org/). Binomial matching with the Plant List and IPNI can be done using a matching algorithm (in software such as R). Species that return multiple matches (using the algorithm) must still be examined and corrections will need to be made one at a time.

It is becoming increasingly common for researchers to work with large continental and global scale data sets (Moles 2005; Chave et al. 2009). The challenge of these databases is that analyses must be preceded by intensive cleaning and filtering and be done with great care and attention to spatial detail (Chapman 1998). However, once those steps are taken, it is equally clear that these are incredibly valuable resources, that provide researchers with direct access to spatial data that is herbarium vouchered and validated. It would be difficult to overstate the value of such data, particularly when it is used in conjunction with analyses designed to examine and compare measures of diversity or endemism, or to look at the phylogenetic signal of diversity across geographic space (Crisp et al. 2001; Laffan & Crisp 2003; Bickford et al. 2004). Once issues around taxonomy (e.g. conspecifics, synonyms and unresolved subspecies) and spatial accuracy are resolved the data become very powerful. For the future, the potential is for the development of web-based flora lists that include similarly accessible tabulated details on a range of informative traits (generally already listed in the text of existing floras). That addition would assist local, continental and global scale studies even further. What is evident is that even in cases where only general patterns are being searched for, such resources provide the potential to uncover some of the most significant secrets of Australia's vegetation.

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Manuscript accepted 4 June 2012

Date of Publication:
30/07/2012

Cunninghamia
A journal of plant ecology for eastern Australia

The Royal
Botanic Gardens
& Domain Trust

ISSN 0727-9620 (print) • ISSN 2200-405X (Online)

# Ephemeral wetlands of the Pilliga Outwash, northwest NSW

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***Abstract***: The floristic composition and vegetation partitioning of the ephemeral wetlands of the Pilliga Outwash within the Pilliga National Park and Pilliga State Conservation Area (30˚30'S, 149˚22'E) on the North Western Plains of New South Wales are described. SPOT5 imagery was used to map 340 wetlands across the Pilliga Outwash. A total of 240 plots within 31 wetlands explored composition and species richness in relation to water depth and wetland size. The predominant community described is the species-rich herbfield of shallow basin wetlands, along with the structurally distinct but the less common sedgeland/herbfield of the deeper 'tank' wetlands and a single wetland with a floristically depauperate *Diplachne fusca* wet grassland. A total of 131 taxa were recorded including three species listed under the NSW Threatened Species Conservation Act (1995): *Eriocaulon australasicum*, *Lepidium monoplocoides* and *Myriophyllum implicatum*. New records for an additional six taxa were recorded for the North Western Plains. 11% of taxa were exotic in origin.

***Cunninghamia* (2012) 12(3): 181–190**
doi: 10.7751/cunninghamia.2012.12.015

## Introduction

Wetland conservation and management requires adequate knowledge of wetland distribution (Kingsford *et al.* 2004), extent and floristic composition. In Australia impermanent wetlands are far more common and widely distributed than are permanent lakes and swamps (Paijmans *et al.* 1985) yet in a global review of ephemeral wetlands (Deil 2005), plot-related data were only available in the literature for Western Australia; for the rest of the continent only general classifications of wetland types were available at that time (Pressey & Adam 1995). To our knowledge, since 2005, information on temporary and ephemeral wetlands has only been collated for some areas of New South Wales (Hunter & Bell 2007; Bell *et al.* 2008; Hunter & Bell 2009). In other areas such as western New South Wales, such information is often only available as part of localized vegetation description (McGann *et al.* 2001), regional vegetation description (Benson *et al.* 2006; Benson *et al.* 2010), or from descriptions of communities establishing from seed banks (James & Capon 2007; Porter *et al.* 2007). Wetland covers 5.6% of New South Wales; of this portion 96% is in western New South Wales (Kingsford *et al.* 2004). Kingsford *et al.* (2004) list six types of spatially derived wetland groups for New South Wales: Freshwater Lakes, Floodplain Wetland, Estuarine Wetland, Saline Lake, Coastal Lagoons and Lakes and Reservoirs. However in the Pilliga Scrub, south west of Narrabri, exist a group of small ephemeral wetlands, that do not conform to these broad wetland types, nor, unsurprisingly, to the broad categories of wetlands described by Keith (2004). The vegetation of these Pilliga wetlands was first described by Benson *et al.* (2010), who named these wetlands Pilliga

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"tank gilgai" wetland sedgeland rushland, Brigalow Belt South Bioregion (Veg. Comm. ID 416), and considered them to be endangered. Coincidentally this wetland community was also described as a separate vegetation community, Tank Herbfields, by floristic analysis within the Pilliga National Park and Pilliga State Conservation Area (Hunter 2010). These initial descriptions were based on a limited amount of data and observation and a limited knowledge of wetland distribution.

The climate of the Pilliga is dry subtropical with moderately dry winters (Benson *et al.* 2010) and the majority of wetlands are likely to fill at most once a decade. Large rainfall events in 2010 through to early 2011 repeatedly filled the wetlands and provided an opportunity for investigation, the intention of which was to circumscribe the location, type and extent of these wetlands, to describe their floristic composition and to put them in context with other wetland types within the region.

## Methods

### *Study area*

The area studied falls within the Brigalow Belt South Bioregion south of the Namoi River Floodplain and forms part of the north western portion of the 500 000 ha Pilliga Scrub which occurs between Coonabarabran, Narrabri and Pilliga. Most of the study area comprises outwash sands, loams and clays resulting primarily from the erosion of upland sandstones further to the south (Keith 2004). Benson *et al.* (2010) described the wetlands as occurring on alkaline sodic grey clay soils with sodic sandy soils in the surrounding Buloke (*Allocasuarina luehmannii*) woodland. Two ephemeral waterways, Goona Creek and Coghill Creek, cross the study area from east to west.

We chose locations within Pilliga National Park and part of the adjoining Pilliga State Conservation Area, in order to investigate wetlands within an area managed for conservation

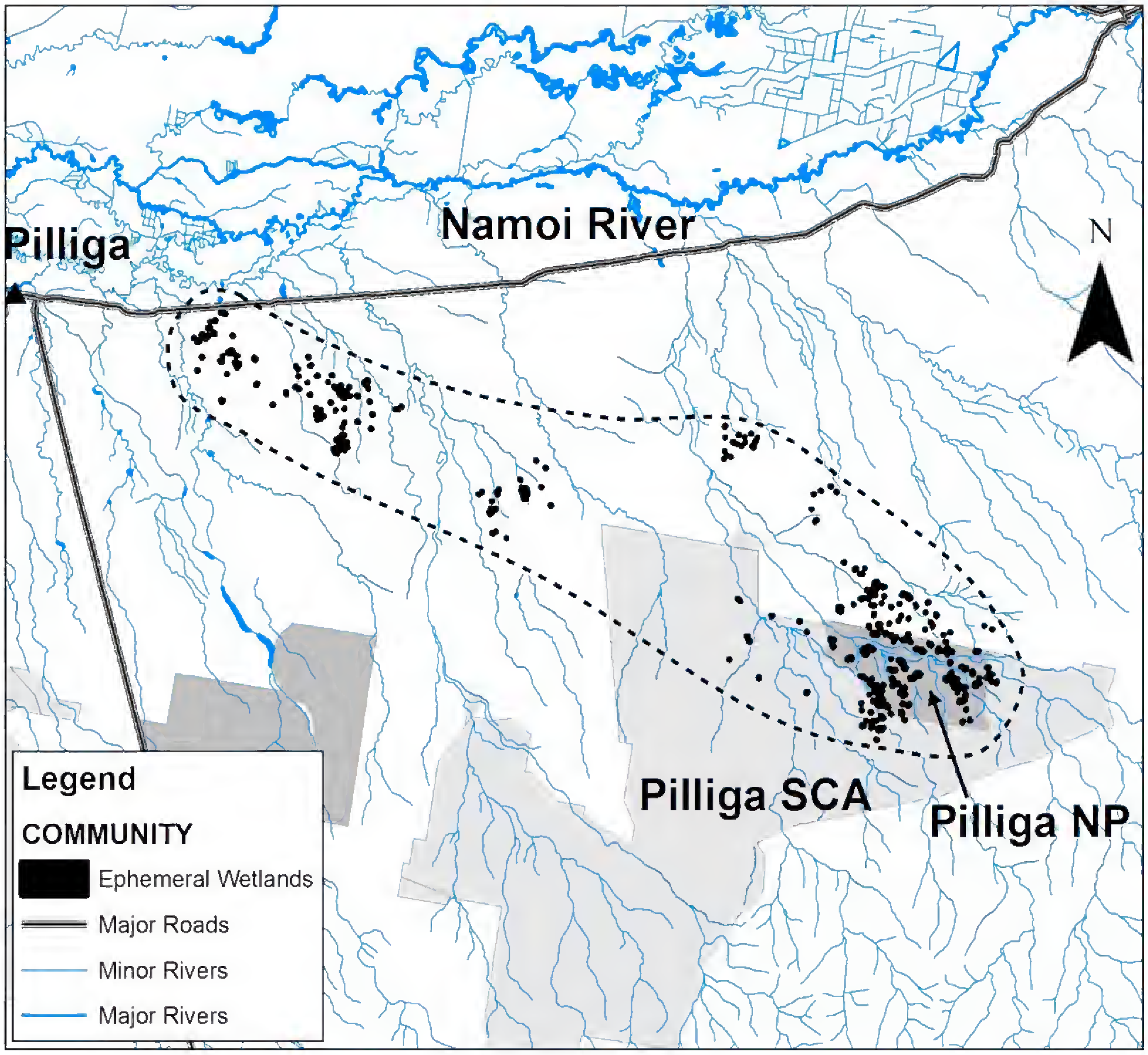

**Fig. 1.** Distribution of ephemeral wetlands in the Pilliga Outwash. The dotted line indicates the extent of the ephemeral wetlands area; wetlands themselves are shown in black, borders are thickened for visibility. Wetlands occur in Pilliga National Park (Pilliga NP), in the surrounding Pilliga State Conservation Area (Pilliga SCA) and in lands to the north and northwest of these. The area bounded by the dotted line measures approximately 40 km by 8 km.

where disturbance is assumed to be more limited. Pilliga State Conservation Area surrounds Pilliga National Park along its eastern, southern and western boundaries (Fig. 1). Pilliga National Park lies approximately 44 km southwest of Narrabri (30° 30' S, 149° 22' E). Rainfall in 2010 was approximately twice the yearly average with the Bureau of Meteorology recording a total of 1119 mm in 2010 for Baradine, southwest of Narrabri, on the western edge of the Pilliga (30° 36' S, 148° 58' E, elevation 211 m, mean annual rainfall 576 mm).

### *Sampling*

Wetland locations were identified using SPOT5 imagery (Fig. 1). Each location was digitized and mapped with ArcGIS 9.3 and Geo-referenced SPOT5 imagery in order to measure areas of individual wetlands using polygons. Wetland size was verified in the field. Ground truthing of all mapped wetlands within Pilliga National Park and Pilliga State Conservation Area was carried out on quad bikes in the early part of the sampling period, to distinguish depressions capable of holding water from other bare but sloping areas such as scalds. From the 107 depressions identified as wetlands, 31 wetlands were chosen for sampling; these covered a range of wetland sizes and locations within the reserves.

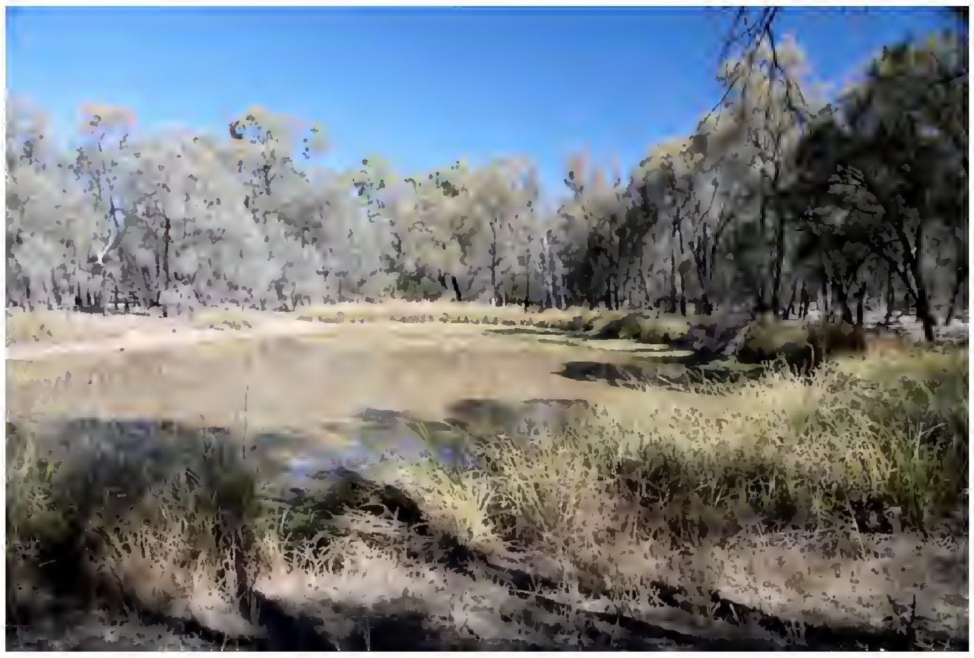

**Fig. 2.** 'Tank' wetland, Pilliga NP, September 2011 (Wetland 96 West, 30°30'24"S, 149°20'15"E).

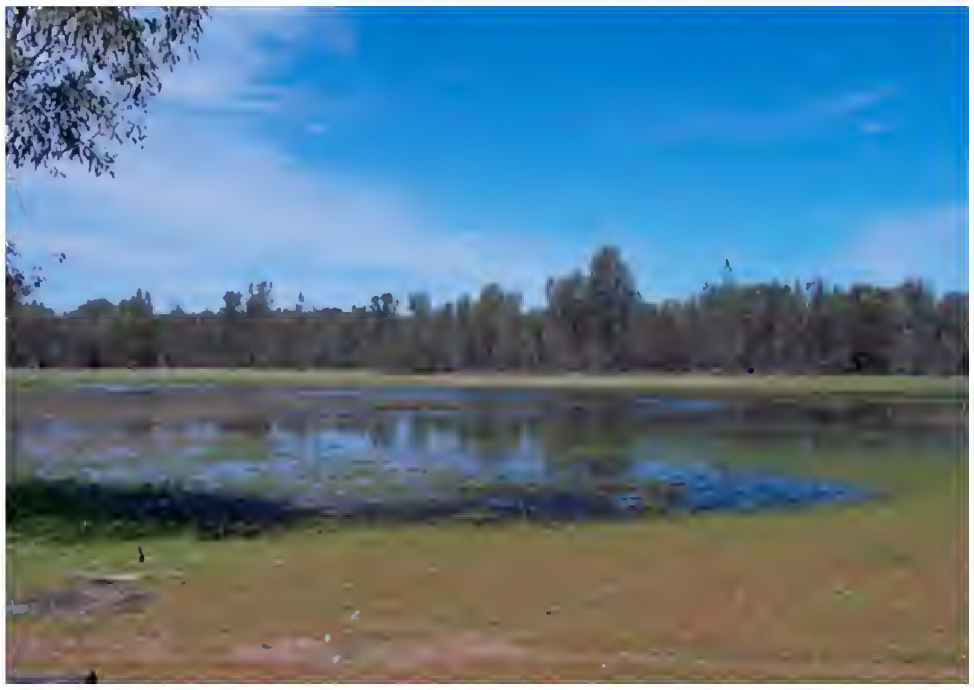

**Fig. 3.** Shallow basin wetland on Old Coghill Road, Pilliga NP, October 2010 (Wetland 37, 30°30'26"S, 149°22'16"E).

In spring–summer 2010–2011, in each of the 31 wetlands, up to three transects were placed in random positions across depth gradients from the edge of the surrounding trees, to the deepest parts of the wetland. Each transect was permanently marked with small posts to allow sites to be revisited. The cover abundance of all vascular species and charophytes on a modified Braun-Blanquet (1982) scale (1–6) was assessed in 2 m x 2 m (4 $m^2$) plots. These plots were placed within visually distinct vegetation bands along each transect (2 to 4 per transect; 240 plots in total). Plot water depths and distance from the starting point were also recorded. Conductivity and pH were measured in five wetlands in March 2011.

Appropriate plant specimens were retained for lodging in the N. C. W. Beadle Herbarium, University of New England with duplicates to the National Herbarium of NSW. Nomenclature follows that of PlantNet (2011) except where recent changes have been published elsewhere.

### *Analyses*

Two data sets were prepared, the first of all plots separately, the second of summed plot data for individual wetlands. Analyses and data exploration were performed using options available in the PATN Analysis Package (Belbin 1995a, b). All species and their cover abundance scores were used and the analysis performed using the Kulczynski association recommended for ecological applications (Belbin 1995a, b) along with flexible UPGMA fusion strategy and the default PATN settings. Community dissimilarity was determined at the 0.85 level.

## Results

340 wetlands were mapped within the broader study area of which 107 occurred within the Pilliga National Park and State Conservation Area (Fig. 1). The total area covered by these wetlands is approximately 121 ha with 92% of wetlands being under 1 ha in size. Wetlands occurred across a 40 km by 8 km ellipse from the Pilliga National Park northwest to near the township of Pilliga (Fig. 1). The wetlands occurred within a mosaic of woodlands and shrublands largely dominated by *Allocasuarina luehmanii, Eucalyptus chloroclada, Eucalyptus pilligaensis, Eucalyptus sideroxylon* and *Melaleuca densispicata* (Benson *et al.* 2010; Hunter 2010).

The wetlands fall into two distinct morphological types; 'tank', and shallow basin wetlands. 'Tank' wetlands are roughly circular to irregularly oblong basins with a distinct lip to 30 cm high, on yellowish soils with higher clay content, often in *Melaleuca densispicata* tall shrubland where extensive scalds are common (Fig. 2). ‘Tank” wetlands usually contain turbid, more permanent water than that of shallow basin wetlands, and can hold water for two to three months. Shallow basin wetlands are on yellowish soils of higher sand content especially at margins. There is a sharp boundary at the woodland edge and shallow basin wetlands are more commonly surrounded by *Allocasuarina luehmannii* (Fig. 3). Water is often, but not always, clear and the smallest wetlands dry in a matter of weeks.

A total of 131 vascular plant taxa in 49 families and 97 genera were recorded in plots and from opportunistic sightings. Four charophyte taxa in the genera *Chara* and *Nitella* were recorded. Families with the most taxa overall were Asteraceae (21 species), Cyperaceae (19 species) and Poaceae (12 species). The richest genera were *Cyperus* (8 species), *Juncus* (6 species) and *Myriophyllum* (4 species).

## Vegetation Assemblages

Three communities were defined in the whole wetland analysis (Figure 4):

### Community 1: *Cyperus gunnii* subsp. *gunnii* – *Nymphoides crenata* sedgeland/herbfield.

**Wetland type**: ‘Tank’ wetland. Turbid open water with a usually continuous 1–2 m wide margin dominated by the tall sedge *Cyperus gunnii* subsp. *gunnii* (height to 1.5 m), occasionally with floating-leaved *Nymphoides crenata* populations in deepest part of basin. As water recedes, a low (0.1–0.2 m) herbfield of ruderal species appears on damp mud.

**Terrestrial and semi terrestrial:** *Eragrostis elongata, Hypericum gramineum, Commelina cyanea, Chloris truncata, Alternanthera denticulata, Sporobolus caroli, Fimbristylis dichotoma, Eragrostis parviflora, Cyperus gracilis, Dichelachne crinita, Dianella revoluta* subsp. *revoluta.*

**Ruderals and mud flat colonisers:** *Glinus oppositifolia, Epaltes australis, Eleocharis pusilla, Lipocarpha microcephala, Cyperus difformis, Chenopodium pumilio, Portulaca filifolia, Fuirena incrassata.*

**Emergents:** *Cyperus gunnii* subsp. *gunnii*, *Myriophyllum simulans, Juncus subsecundus, Eleocharis macbarroni, Juncus psammophilus, Philydrum lanuginosum, Eleocharis plana, Mitrasacme paludosa, Diplachne fusca, Cyperus betchei* subsp *betchei.*

**Floating-leaved:** *Nymphoides crenata*.

**Submerged**: None.

**Exotics:** *Bidens pilosa, Gomphrena celosioides, Spergularia rubra, Xanthium occidentale.*

**Variability**: Sometimes *Cyperus gunnii* subsp. *gunnii* margin not intact, margins not so distinctly lipped. Generally less species-rich (9 to 20 species per wetland) than Community 2.

### Community 2: *Eleocharis pusilla* – *Myriophyllum simulans* – *Nymphoides crenata* – *Marsilea hirsuta* – *Pseudoraphis spinescens* herbfield/sedgeland with an ephemeral component dominated by *Goodenia gracilis* – *Centipeda minima* subsp. *minima* – *Gratiola pedunculata* – *Alternanthera denticulata*.

**Wetland type**: Shallow basin wetlands.

**Terrestrial and semi terrestrial:** *Eragrostis elongata*, *Hypericum gramineum* s.lat.,*Wahlenbergia tumidifructa*, *Wahlenbergia gracilis*, *Bulbine semibarbata*, *Commelina cyanea*, *Ophioglossum lusitanicum*, *Fimbristylis dichotoma*, *Walwhalleya subxerophylla*, *Chamaesyce drummondii*, *Murdannia graminea*, *Rumex tenax*, *Plantago turrifera*, *Lepidium monoplocoides*, *Portulaca oleracea*, *Chloris truncata*.

**Ruderals and mud flat colonisers:** *Goodenia gracilis*, *Centipeda minima* subsp. *minima*, *Epaltes australis*, *Gratiola pedunculata*, *Alternanthera denticulata*, *Myriophyllum implicatum*, *Calandrinia pumila*, *Peplidium foecundum*, *Calandrinia eremaea*, *Brachyscome goniocarpa*, *Crassula sieberiana*, *Ranunculus sessiliflorus* var.

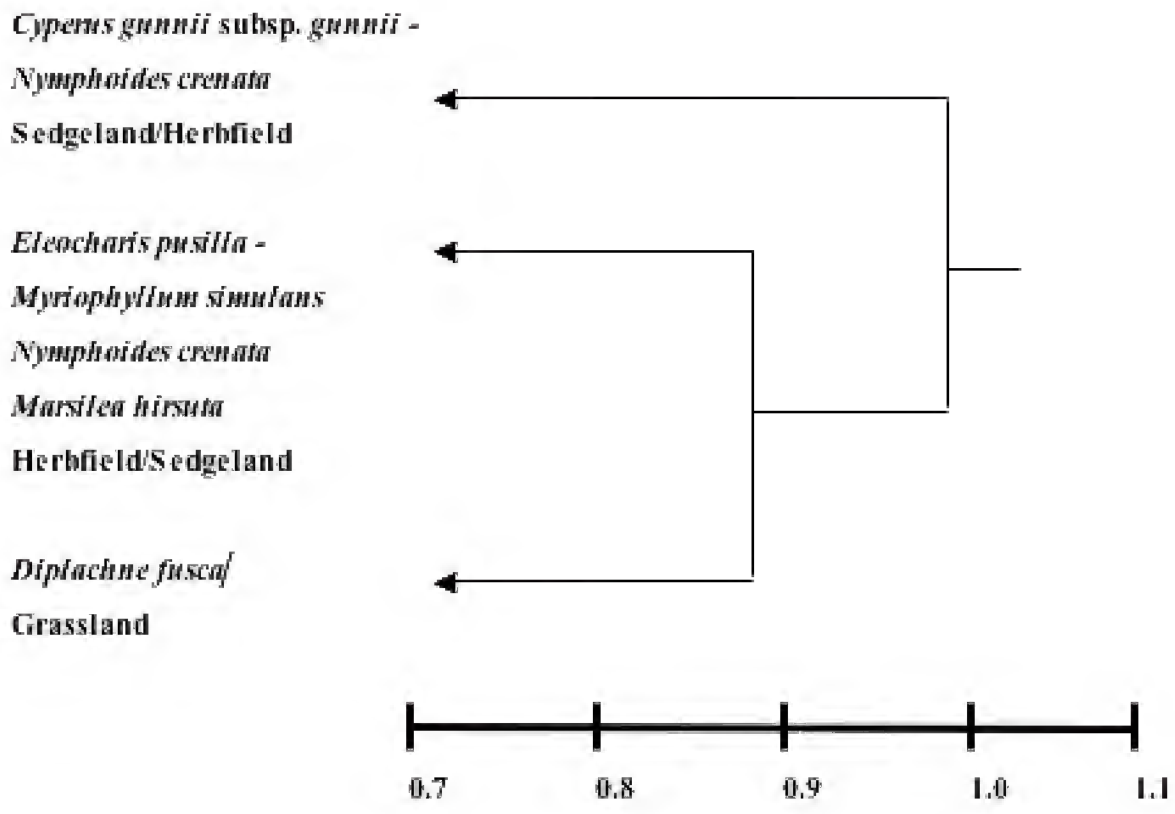

**Fig. 4.** Summary dendrogram of 31 ephemeral wetlands surveyed within Pilliga NP and Pilliga State Conservation Area using Kulczynski association and flexible UPGMA fusion strategy. Communities have been defined at a dissimilarity level of c. 0.85.

*pilulifer*, *Carex inversa*, *Cyperus flaccidus*, *Elatine gratioloides*, *Cyperus squarrosus*, *Centrolepis strigosa* subsp. *strigosa*, *Centipeda thespidioides*, *Eriocaulon australasicum*, *Lipocarpha microcephala*, *Drosera indica*, *Isolepis hookeriana*, *Myriocephalus pluriflorus*, *Centrolepis eremica*, *Helichrysum luteoalbum*, *Lachnagrostis filiformis*, *Cyperus difformis*, *Callitriche sonderi*, *Triglochin calcitrapa*, *Juncus bufonius*, *Portulaca filifolia*, *Fuirena incrassata*, *Calotis hispidula*, *Senecio glossanthus*, *Plantago turrifera*, *Myriocephalus rhizocephalus*, *Myosurus australis*, *Triptilodiscus pygmaeus*, *Polygonum plebeium*, *Cyperus sanguinolentus*, *Lythrum hyssopifolia*, *Euchiton sphaericus*, *Brachysome multifida* var. *multifida*, *Portulaca bicolor* var. *rosea*, *Drosera peltata*, *Drosera burmanni*.

**Emergents:** *Eleocharis pusilla*, *Myriophyllum simulans*, *Cyperus gunnii* subsp. *gunnii*, *Glossostigma diandrum*, *Marsilea hirsuta*, *Pseudoraphis spinescens*, *Isoetes muelleri*, *Hydrocotyle tripartita*, *Juncus subsecundus*, *Mimulus gracilis*, *Mitrasacme paludosa*, *Isotoma fluviatilis* subsp. *borealis*, *Eleocharis plana*, *Marsilea costulifera*, *Myriophyllum verrucosum*, *Diplachne fusca*, *Cynodon dactylon*, *Eleocharis pallens*, *Utricularia dichotoma*, *Schoenus apogon*, *Philydrum lanuginosum*, *Rorippa laciniata*, *Juncus psammophilus*, *Juncus aridicola*, *Juncus flavidus*, *Eryngium paludosum*, *Eleocharis macbarronii*, *Amphibromus nervosus*, *Cyperus rigidellus*, *Cyperus gymnocaulos*, *Cyperus betchei* subsp. *betchei*, *Juncus ochrocoleus.*

**Floating-leaved:** *Nymphoides crenata*, *Nymphoides geminata*, *Potamogeton sulcatus*, *Ottelia ovalifolia* subsp. *ovalifolia*, *Damasonium minus*, *Triglochin multifructa*.

**Submerged**: *Najas tenuifolia, Vallisneria australis*, *Chara fibrosa*, *Chara* sp., *Nitella sonderi, Nitella* sp.

**Exotics:** *Soliva anthemifolia, Schoenoplectus erectus*, *Sisyrinchium* sp. A, *Sagina apetala*, *Conyza bonariensis*, *Cuscuta campestris*, *Gamochaeta coarctata*, *Spergularia rubra*, *Veronica peregrina*, *Anagallis arvensis*, *Gomphrena celosioides*, *Xanthium occidentale*, *Vulpia bromoides*, *Sonchus oleraceus*, *Gamochaeta calviceps*, *Centaurea melitensis.*

**Variability**: This community occurred in wetlands varying greatly in both size (<0.05 to 3.6 ha) and depth (0 to >70 cm, although the lower limit is misleading since a few very shallow wetlands were dry when sampled). Species richness per wetland was also highly variable (8 to 42 species) and appeared to bear no relationship to either wetland size or wetland depth. Some quite small wetlands were species-rich, others species-poor; the most species-rich wetland was relatively large but other large wetlands were species-poor.

### Community 3: *Diplachne fusca* grassland.

**Wetland type**: Sampled at a single site. Species-poor, very shallow basin wetland, sandy sloping margins.

**Terrestrial and semi terrestrial:** *Lepidium monoplocoides*.

**Ruderals and mud flat colonisers:** *Calandrinia eremaea*, *Epaltes australis*.

**Emergents:** *Diplachne fusca, Cynodon dactylon.*

**Floating-leaved:** None.

**Submerged**: None.

**Exotics:** *Spergularia rubra.*

**Variability**: Not known.

### *Species richness*

Plot species richness across wetland depth gradients (as distinct from richness in whole wetlands) was highly variable. Plots in the deepest parts of the wetlands generally had lower species richness (1–5/4m$^2$) but variability in plots on damp soil was very high (3–27/4m$^2$) and did not appear to vary with wetland size. Whole wetland richness varied from eight in one of the smallest wetlands to 54 in one of the largest.

The water in wetlands sampled in March 2011 was slightly acid to slightly alkaline (pH 6.4 to 7.9). Water quality in partially dry wetlands was good with conductivity ranging from 181 uS/cm to 510 uS/cm.

## Discussion

Two distinct communities relating to basin geomorphology (and an additional depauperate single wetland community) are described for the wet phase of these wetlands. Community 2 (*Eleocharis pusilla – Myriophyllum simulans – Nymphoides crenata – Marsilea hirsuta – Pseudoraphis spinescens* herbfield/sedgeland) occurs in broad gently sloping basins. As water recedes from the edges of this basin, the species-rich ephemeral component (*Eleocharis pusilla*, *Goodenia gracilis*, *Centipeda minima* subsp. *minima*, *Epaltes australis*, *Isoetes muelleri)* is established towards the margins and in central deeper areas, a few true aquatics (submerged, floating-leaved and emergents e.g. *Najas tenuifolia*, *Potamogeton sulcatus* and *Triglochin procera*) are found especially in clear water (Fig. 5). In some wetlands the deeper water has a monoculture of *Myriophyllum simulans* with the edges a monoculture of *Eleocharis* pusilla with a smattering of other species. Species richness per plot is much reduced in the dry phase; in one of the largest wetlands, the wet phase had more than twice the species richness of the dry phase (Benson *et al.* 2010; Hunter 2010). There are also some compositional differences between wet and dry phases (see Appendix). These ephemeral wetlands are more species rich than the semi-permanent upland wetlands of the Northern Tablelands (Bell *et al.* 2008). In this sampling season 72 species occurred in the four largest Pilliga Outwash wetlands compared to 47 species for one sampling season in five upland wetlands (D. Bell, unpublished data).

### *Morphology*

The local name for these wetlands is ‘gilgai’, ‘tank gilgai’ or simply ‘tanks’. Gilgais are soil surface undulations in desert landscapes that result from differential movements of clay soil blocks (Hallsworth *et al.* 1955; Beadle 1981). The distinctive lattice gilgai patterns on the grey cracking clays under Brigalow to the north and northwest of Pilliga National Park and Pilliga State Conservation Area can clearly be distinguished on SPOT5 imagery from the less patterned and more random ephemeral wetlands of the Pilliga Outwash; it is unlikely that Pilliga Outwash wetlands are formed through gilgai processes (Jim Charley pers. comm.). The geology of Pilliga National Park is sand plain, with sand predominant, gravel, and clay; the geology northwest is channel and floodplain alluvium (Atlas of NSW 2011). Outwash wetlands are thought to be depressions originating from former billabongs or ponds left over from ancient drainage lines, with the 'tank' depressions possibly from more recent streams and their associated wetlands (Jim Charley pers. comm.). Similar ponds occur sporadically today along Coghill Creek.

### *Variability*

Multiple levels of variability in the sampling data relate to the timing of rainfall events, sampling times, salinity and possibly to metapopulation dynamics. There is a degree of unpredictability in whole wetland species richness not apparently related to wetland size. There was no obvious explanation for some small wetlands (and some large) having many species and others not. Some wetlands may have more sodic soils limiting them to more salt tolerant species or the discrepancies may be due solely to chance. Opportunistic colonization or extinction theoretically could result in smaller population sizes, since filling events are highly stochastic and localized. Some wetlands were no doubt sampled at an early establishment phase since filling; others at a later stage when herbfields were well established. These are common methodological issues for sampling in aseasonal ephemeral wetlands. The isolation in space of some of the wetland populations may also limit dispersal of some species and result in their limitation to certain wetlands. Further exploration of the elements of this variability could involve further sampling in both wet and dry phases and soil and water testing.

### *Wetting/drying regime*

Details of the depth, frequency, duration, extent and variability of filling of these wetlands are as yet unknown, and likely to be unpredictably stochastic. We presume that the wetlands only fill from overland flow after extraordinary rainfall events or series of events, but partially fill or remain damp for some time after any reasonably large rainfall event. Seed banks of ruderal species are no doubt replenished as a result of these smaller events but true aquatics (deep water floating-leaved, submerged and emergents) rely on long-term persistence of seeds, tubers (*Triglochin multifructa*) or rhizomes (*Juncus*, *Cyperus gunnii* subsp. *gunnii*) in the soil.

Rainfall is not only sporadic but usually highly localized so that some wetlands fill while others may remain dry. That fraction that fills allow species to complete life cycles and contribute to persistence of these wetland communities in the landscape.

### *Similarities to other wetlands*

These small but discrete lentic wetlands are found only within that relatively small area of the Pilliga Scrub towards the northwestern edge of the Pilliga Outwash and are generally associated with closely patterned ephemeral creeks and waterways (Figure 1). In the area searched on SPOT 5 imagery (between Pilliga township, the Namoi River and Narrabri in the north and the Pilliga sandstone escarpment in the south), the only other lentic wetlands detected were occasional dams, the much larger Yarrie Lake and the distinctly patterned lattice gilgae on heavy clays. Shallow ephemeral wetlands with sporadic wetting and drying cycles are however not unique to the Pilliga. Although mostly undescribed (but see McGann *et al.* 2001), ephemeral wetlands are known to occur in other semiarid to arid parts of NSW (see Porter *et al.* 2007). But we are unaware of any that are numerous enough to form aggregations in such a relatively small area and on such distinctive geomorphology.

### *Growth form types*

Growth form types encountered in these wetlands are similar to those of ephemeral wetlands worldwide: dwarf annuals or short-lived species such as *Eleocharis pusilla, Crassula sieberiana, Eriocaulon australasicum, Centrolepis eremica,*

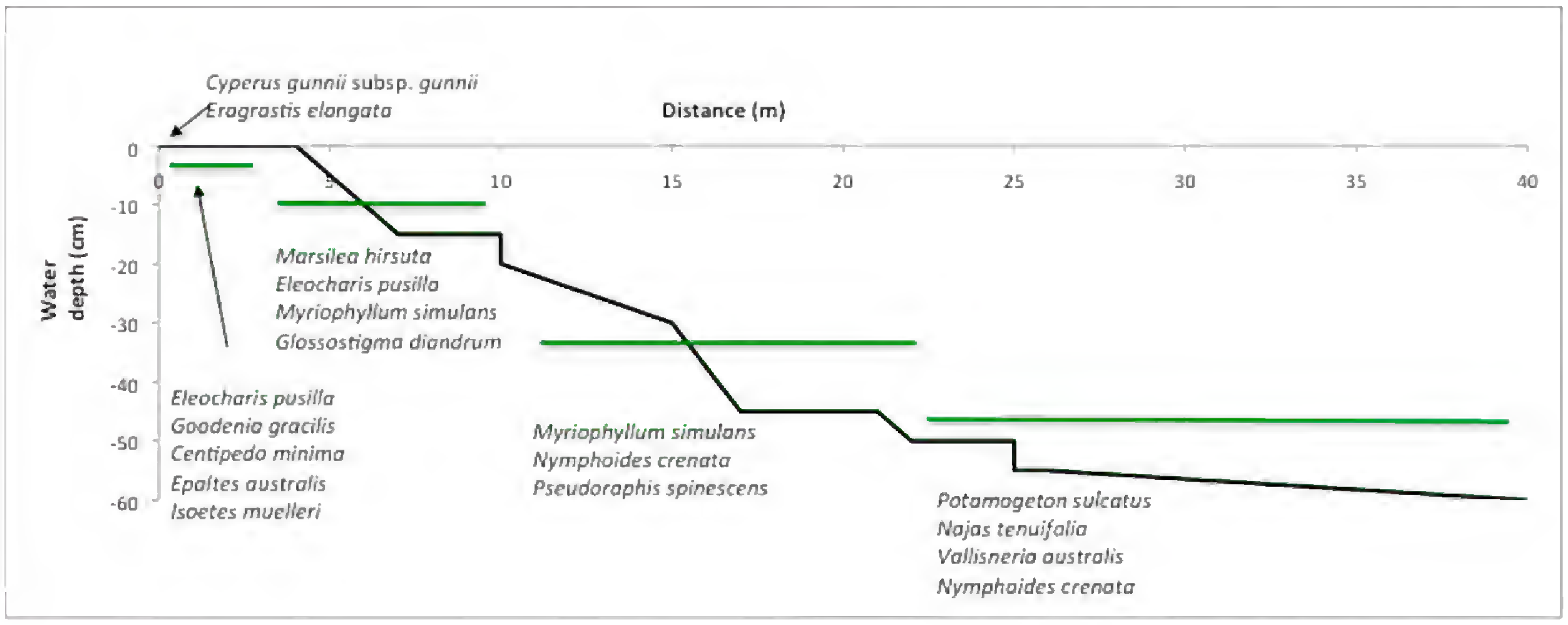

**Fig. 5.** Typical Community 2 changes in dominant species along a water depth gradient in two large shallow basin wetlands. The black line indicates changes in water depth; the green line distributional changes in dominant species with depth and distance from wetland margins.

*Callitriche sonderi, Ranunculus sessiliflorus* and geophytic perennials (species with persistent bases) such as *Isoetes muelleri* and *Ophioglossum lusitanicum* (Deil 2005). Many more species are ruderal or short-lived rather than perennial and of those species establishing on damp soil few are clonal (e.g. *Eleocharis pusilla*), in contrast to the strictly clonal aquatic species of the deeper water. Not all species in the ephemeral herbfield component are wetland specialists but belong to those taxa encountered on damp soils in many other situations such as in riparian areas and drainage depressions (e.g. *Epaltes australis*).

### *Former land-use*

The wetlands, especially the 'tank' wetlands, appear to have been of use as a bare (i.e. tree-free) area by pastoralists. The remains of a small stockyard was seen in one wetland; others have remnants of fencing around them and were apparently used with a rough one-way gate to trap and herd cattle. One or two others provided an open area for cutting and stacking sleepers.

### *Species significance*

Three species currently listed on the NSW *Threatened Species Conservation Act* 1995 were found within the wetlands and six others were considered regionally significant. The small annual herb *Eriocaulon australasicum* (Family Eriocaulaceae) was occasional to common in plots in four of the wetlands surveyed; this species is listed as Endangered, both federally (EPBC Act) and statewide (TSC Act), and in ROTAP (3V). There was a very early collection along the Murray River in New South Wales (OE&H 2011a; PlantNet 2011). *Eriocaulon australasicum* is known from a few populations in Victoria and adjoining South Australia.

The annual herb *Lepidium monoplocoides* (Family Brassicaceae), found scattered at wetland margins, is listed as Endangered both federally (EPBC Act) and statewide (TSC Act) and in ROTAP (3ECi) and is known from semi-arid regions of New South Wales, Victoria and possibly South Australia.

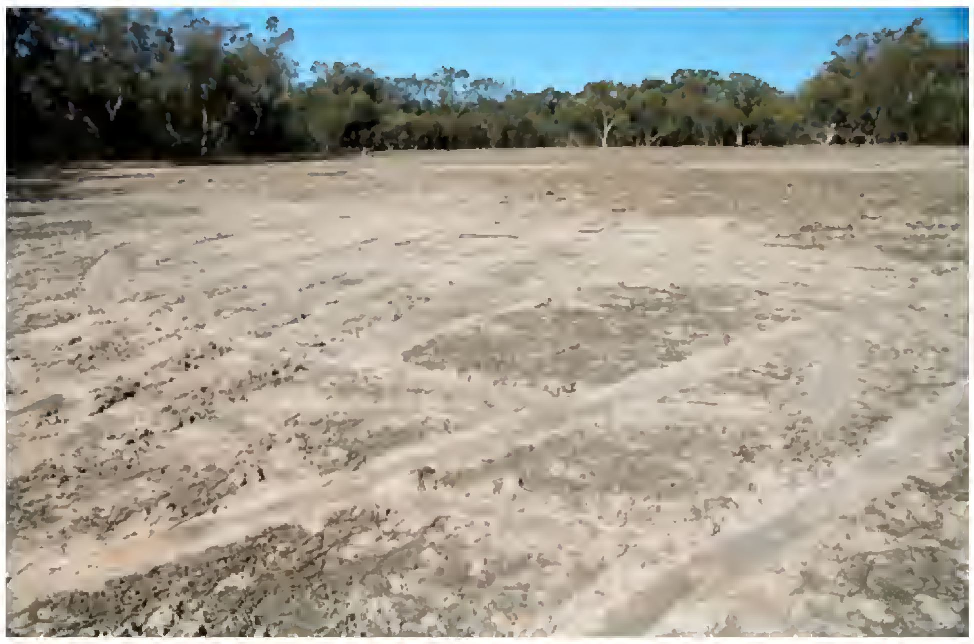

**Fig. 6.** Soil disturbance by recreational vehicles in a shallow basin wetland, Pilliga NP, September 2011 (Wetland 98, 30°30'15"S, 149°20'27"E).

*Myriophyllum implicatum* (Family Haloragaceae), a strictly dioecious creeping herb (Orchard 1985) that forms discrete mats on damp mud and can tolerate shallow water, was found in four localized shallow basin wetlands, in one of which it was the dominant species in an extensive band near the water's edge. *Myriophyllum implicatum* is usually confined to coastal areas in south-eastern Queensland with an undated record from the Hastings River in north-eastern New South Wales (OE&H 2011b) and was considered extinct in New South Wales until collected in 2008 by John Benson during surveys in the Pilliga Region (Benson *et al.* 2010; PlantNet 2011).

Six species are considered regionally significant since they are disjunct or thought to be at or near their geographic limits. These taxa are: *Centrolepis eremica*, *Drosera burmanni*, *Hydrocotyle tripartita*, *Isoetes muelleri*, *Peplidium foecundum* and *Philydrum lanuginosum*. Of interest also are the *Nymphoides geminata* populations. *Nymphoides geminata* is usually homostylous but populations in the Pilliga Outwash are consistently heterostylous.

### *Soil disturbance*

Soil disturbance risks both disruption of the seed bank by deeper burial of seeds and encouragement of weedy species. Minor to extensive digging by wild pigs was seen in almost all wetlands in 2010; pig wallows in deep holes were also seen in September 2011. In addition, the soil surface of the more accessible wetlands shows evidence of deep wheel tracks of recreational vehicles (Fig. 6). Trampling and grazing by stray cattle, feral goats and horses are also potential threats to soil stability.

A plume of deposited soil from the erosion of a gully and scald close to the northern boundary has the potential to enlarge and to ultimately fill one of the 'tank' wetlands. Road construction in or near wetlands is also a potential threat.

### *Road construction and hydrological change*

A road has been constructed through the middle of one of the mapped shallow basin wetlands with associated roadside drains and additional drains elsewhere in the basin. During a drought in late 2010 this drained wetland was described as an ephemeral herbfield but with almost none of the ephemeral wetland flora described for Community 2 (Hunter 2010). Hunter (2010) described this community as a derived herbfield dominated by *Tripogon loliiformis* and *Enteropogon acicularis,* floristically distinct from the *Bulbine semibarbata – Calandrinia eremaea* herbfield in an intact wetland sampled during the same survey. Some wetlands on private property to the north and northwest appear to have been made more permanent by impoundment.

### *Weeds*

Only 11% of taxa sampled during this survey were exotic. Of these the small sedge *Schoenoplectus erectus* is known to cause problems elsewhere (Benson *et al.* 2010), but is not as yet a common component of these wetland communities.

### *Conservation*

We recommend that these ephemeral wetland communities be considered endangered in New South Wales. Benson *et al.* (2010) states that they are inadequately protected and gives them the threat category Endangered (E/3c threat criteria 2,4). These wetlands are relatively rare and localized in the Pilliga Outwash landscape and are morphologically distinct from and should not be confused with the more common lattice gilgai depressions on grey cracking clays under Brigalow on lands to the north and northwest. Only one third of the mapped wetlands occur in reserves. Further addition of lands to reserves or voluntary conservation agreements would be beneficial to conservation, as well as population studies of threatened species and monitoring of weed invasion. Protection from recreational vehicles, pig control and sedimentation is urgently required. Revisiting and sampling the permanently marked sites in both wet and dry phases would provide additional knowledge on the vegetation dynamics of these communities.

## Acknowledgements

The NSW Office for Environment and Heritage at Baradine is thanked for providing vehicles and staff to assist the survey. Sincere thanks are also due to Shane Edmonstone who assisted the third author in quad bike ground-truthing of wetlands, and to Kate Smiley, Daniel Bailey, and Jon Burne for assistance with fieldwork. Ian Telford of the N. C. W. Beadle Herbarium, University of New England and John Hosking are thanked for assistance with species nomenclature and identification.

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Manuscript accepted 2 April 2012

**Appendix 1**. Vascular species and charophytes of Pilliga Outwash ephemeral wetlands. Community 1 is sedgeland/herbfield of 'tank' wetlands; 2: herbfield/sedgeland with an ephemeral component in shallow basin wetlands; 3. *Diplachne fusca* grassland. Exotic taxa are prefixed with an asterisk. Small letters indicate species named in other surveys or recorded opportunistically: a: Benson (2010), b: Hunter (2010), o: opportunistic.

| | C1 | C2 | C3 | Other |
|---|---|---|---|---|
| ALGAE | | | | |
| Characeae | | | | |
| *Chara fibrosa* | | 1 | | |
| *Chara* sp. | | 1 | | |
| *Nitella sonderi* | | 1 | | |
| *Nitella* sp. | | 1 | | |
| FERNS AND FERN ALLIES | | | | |
| Isoetaceae | | | | |
| *Isoetes muelleri* | | 1 | | |
| Marsileaceae | | | | |
| *Marsilea costulifera* | | 1 | | |
| *Marsilea drummondii* | | | | a |
| *Marsilea hirsuta* | | 1 | | |
| Ophioglossaceae | | | | |
| *Ophioglossum lusitanicum* | | 1 | | |
| MONOCOTYLEDONS | | | | |
| Asphodelaceae | | | | |
| *Bulbine semibarbata* | | 1 | | |
| Centrolepidaceae | | | | |
| *Centrolepis eremica* | | 1 | | |
| *Centrolepis strigosa* subsp. *strigosa* | | 1 | | |
| Commelinaceae | | | | |
| *Commelina cyanea* | 1 | 1 | | |
| *Murdannia graminea* | | 1 | | |
| Cyperaceae | | | | |
| *Carex inversa* s. lat. | | 1 | | |
| *Cyperus betchei* subsp. *betchei* | 1 | 1 | | |
| *Cyperus difformis* | 1 | 1 | | |
| *Cyperus flaccidus* | | 1 | | |
| *Cyperus gunnii* subsp. *gunnii* | 1 | 1 | | |
| *Cyperus gymnocaulos* | | 1 | | |
| *Cyperus rigidellus* | | 1 | | |
| *Cyperus sanguinolentus* | | 1 | | |
| *Cyperus squarrosus* | | 1 | | |
| *Eleocharis macbarronii* | 1 | | | |
| *Eleocharis pallens* | | 1 | | |
| *Eleocharis plana* | 1 | 1 | | |
| *Eleocharis pusilla* | 1 | 1 | | |
| *Fimbristylis dichotoma* | 1 | 1 | | |
| *Fuirena incrassata* | 1 | 1 | | |
| *Isolepis hookeriana* | | 1 | | |
| *Lipocarpha microcephala* | 1 | 1 | | |
| **Schoenoplectus erectus* | | 1 | | |
| *Schoenus apogon* | | 1 | | |
| Eriocaulaceae | | | | |
| *Eriocaulon australasicum* | | 1 | | |
| Hydrocharitaceae | | | | |
| *Ottelia ovalifolia* subsp. *ovalifolia* | | 1 | | |
| *Vallisneria australis* | | 1 | | |
| Iridaceae | | | | |
| **Sisyrinchium* sp. A | | 1 | | |
| Juncaceae | | | | |
| *Juncus aridicola* | | 1 | | |
| *Juncus bufonius* | | 1 | | |
| *Juncus continuus* | | | | a |
| *Juncus flavidus* | | 1 | | |
| *Juncus ochrocoleus* | | 1 | | |
| *Juncus psammophilus* | 1 | 1 | | |
| *Juncus subsecundus* | 1 | 1 | | |
| Juncaginaceae | | | | |
| *Triglochin calcitrapa* | | 1 | | |
| *Triglochin multifructa* | | | | o |
| Najadaceae | | | | |
| *Najas tenuifolia* | | 1 | | |
| Philydraceae | | | | |
| *Philydrum lanuginosum* | 1 | 1 | | |
| Phormiaceae | | | | |
| *Dianella revoluta* subsp. *revoluta* | 1 | | | |
| Poaceae | | | | |
| *Amphibromus nervosus* | | 1 | | |
| *Chloris truncata* | 1 | 1 | | |
| *Cynodon dactylon* | | 1 | 1 | |
| *Dichelachne micrantha* | 1 | | | |
| *Diplachne fusca* | 1 | 1 | 1 | |
| *Eragrostis elongata* | 1 | 1 | | |
| *Eragrostis parviflora* | 1 | | | |
| *Eragrostis speciosa* | | | | o |
| *Lachnagrostis filiformis* | | 1 | | |
| *Panicum decompositum* | | | | a |
| *Pseudoraphis spinescens* | | 1 | | |
| *Sporobolus caroli* | | | | |
| **Vulpia bromoides* | | 1 | | |
| *Walwhalleya subxerophila* | | 1 | | |
| Potamogetonaceae | | | | |
| *Potamogeton sulcatus* | | 1 | | |
| DICOTYLEDONS | | | | |
| Aizoaceae | | | | |
| *Glinus oppositifolius* | 1 | | | |
| Alismataceae | | | | |
| *Damasonium minus* | | 1 | | |
| Amaranthaceae | | | | |
| *Alternanthera denticulata* | 1 | 1 | | |
| **Gomphrena celosioides* | 1 | 1 | | |
| Apiaceae | | | | |
| *Eryngium paludosum* | | 1 | | |
| *Hydrocotyle tripartita* | | 1 | | |
| Asteraceae | | | | |
| **Bidens pilosa* | 1 | | | |
| *Brachyscome ciliaris* var. *subintegrifolia* | | 1 | | |
| *Brachyscome goniocarpa* | | 1 | | |
| *Brachyscome heterodonta* | | | | b |

| | | | | |
|---|---|---|---|---|
| *Brachysome multifida* var. *multifida* | | 1 | | |
| *Brachyscome nodosa* | | | | a |
| *Calotis hispidula* | | 1 | | |
| *Calotis* sp. | | 1 | | |
| **Centaurea melitensis* | | 1 | | |
| *Centipeda cunninghamia* | | | | b |
| *Centipeda minima* subsp. *minima* | | 1 | | |
| *Centipeda thespidioides* | | 1 | | |
| **Conyza bonariensis* | | 1 | | |
| *Epaltes australis* | 1 | 1 | 1 | |
| *Euchiton sphaericus* | | 1 | | |
| **Gamochaeta calviceps* | | 1 | | |
| **Gamochaeta coarctata* | | 1 | | |
| *Helichrysum luteoalbum* | | 1 | | |
| *Lemooria burkittii* | | | | b |
| *Myriocephalus pluriflorus* | | 1 | | |
| *Myriocephalus rhizocephalus* | | 1 | | |
| *Senecio glossanthus* | | 1 | | |
| **Soliva anthemifolia* | | 1 | | |
| **Sonchus oleraceus* | | 1 | | |
| *Triptilodiscus pygmaeus* | | 1 | | |
| **Xanthium occidentale* | 1 | 1 | | |
| Brassicaceae | | | | |
| *Lepidium monoplocoides* | | 1 | 1 | |
| *Rorippa laciniata* | | 1 | | |
| Callitrichaceae | | 1 | | |
| *Callitriche sonderi* | | 1 | | |
| Campanulaceae | | | | |
| *Wahlenbergia gracilenta* | | | | b |
| *Wahlenbergia gracilis* | | 1 | | |
| *Wahlenbergia tumidifructa* | | 1 | | |
| Caryophyllaceae | | | | |
| **Sagina apetala* | | 1 | | |
| **Spergularia rubra* | 1 | 1 | 1 | |
| Casuarinaceae | | | | |
| *Allocasuarina luehmannii* | | 1 | | |
| Chenopodiaceae | | | | |
| *Chenopodium pumilio* | 1 | | | |
| *Dysphania glomulifera* subsp. *glomulifera* | | | | o |
| Clusiaceae | | | | |
| *Hypericum gramineum* s.lat. | 1 | 1 | | |
| Convolvulaceae | | | | |
| **Cuscuta campestris* | | 1 | | |
| Crassulaceae | | | | |
| *Crassula sieberiana* | | 1 | | |
| Droseraceae | | | | |
| *Drosera burmannii* | | 1 | | |
| *Drosera indica* | | 1 | | |
| *Drosera peltata* | | 1 | | |
| Elatinaceae | | | | |
| *Elatine gratioloides* | | 1 | | |
| Euphorbiaceae | | | | |
| *Chamaesyce drummondii* | | 1 | | |
| Gentianaceae | | | | |
| **Centaurium tenuiflorum* | | 1 | | |
| Goodeniaceae | | | | |
| *Goodenia gracilis* | | 1 | | |
| *Goodenia* sp. | | | | |
| Haloragaceae | | | | |
| *Myriophyllum implicatum* | | 1 | | |
| *Myriophyllum simulans* | 1 | 1 | | |
| *Myriophyllum striatum* | | | | a |
| *Myriophyllum verrucosum* | | 1 | | |
| Lentibulariaceae | | | | |
| *Utricularia dichotoma* | | 1 | | |
| Lobeliaceae | | | | |
| *Isotoma fluviatilis* subsp. *borealis* | | 1 | | |
| Loganiaceae | | | | |
| *Mitrasacme paludosa* | 1 | 1 | | |
| Lythraceae | | | | |
| *Lythrum hyssopifolia* | | 1 | | |
| Menyanthaceae | | | | |
| *Nymphoides crenata* | 1 | 1 | | |
| *Nymphoides geminata* | | 1 | | |
| Myrtaceae | | | | |
| *Eucalyptus chloroclada* | | 1 | | |
| Plantaginaceae | | | | |
| *Plantago turrifera* | | 1 | | |
| Polygonaceae | | | | |
| *Polygonum plebeium* | | 1 | | |
| *Rumex tenax* | | 1 | | |
| Portulacaceae | | | | |
| *Calandrinia eremaea* | | 1 | 1 | |
| *Calandrinia pumila* | | 1 | | |
| *Portulaca bicolor* var. *rosea* | | | | |
| *Portulaca filifolia* | 1 | 1 | | |
| *Portulaca oleracea* | | 1 | | |
| Primulaceae | | 1 | | |
| **Anagallis arvensis* | | 1 | | |
| Ranunculaceae | | | | |
| *Myosurus minimus* var. *australis* | | 1 | | |
| *Ranunculus sessiliflorus* var. *pilulifer* | | 1 | | |
| Scrophulariaceae | | | | |
| *Glossostigma diandrum* | | 1 | | |
| *Gratiola pedunculata* | | 1 | | |
| *Mimulus gracilis* | | 1 | | |
| *Peplidium foecundum* | | 1 | | |
| **Veronica peregrina* | | 1 | | |

Date of Publication:
30/07/2012

Cunninghamia
A journal of plant ecology for eastern Australia

The Royal
Botanic Gardens
& Domain Trust

ISSN 0727-9620 (print) • ISSN 2200-405X (Online)

# Understanding the characteristics of a groundwater-dependent ecosystem: *Eucalyptus parramattensis* Woodland at Porters Creek Wetland, NSW

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***Abstract*:** Little is known about groundwater-dependent ecosystems in south-eastern Australia and few studies have examined the impact of landclearing upslope of such ecosystems. The eastern edge of Porters Creek wetland, near Warnervale on the Central Coast of New South Wales, supports a *Eucalyptus parramattensis* subsp. *parramattensis* (Parramatta Red Gum) population. The population has been listed as an Endangered Population (EP) and was showing signs of dieback during the 2002 to mid-2007 drought. Water table depth, soil moisture tension, soil temperature and groundwater salinity beneath this woodland were measured to investigate whether the woodland is associated with a shallow aquifer and/or high soil moisture conditions, and whether an upslope construction development would impact on the ecosystem. The composition, structure and health of the *Eucalyptus parramattensis* Woodland was also examined.

Monitoring over 5 years demonstrated that *Eucalyptus parramattensis* is associated with a shallow, slightly saline to saline (8–12 ppt) water table, 1.4–3.1 m beneath the surface of a drainage depression wetland. During the drought water table drawdown rates were quite rapid, and rainfall events took up to a month to replenish water table levels. Landclearing for an upslope development significantly decreased the average water table level by 0.3–0.5 m during the construction phase, while peaks that occurred at the base of the slope after large rainfall events reversed the normal direction of the water table gradient. The water table re-stabilised to pre-construction levels after construction was completed and the area was landscaped and revegetated with grass. The short-term alteration of groundwater conditions did not appear to impact on tree health; the poor tree health observed prior to construction was most likely due to the lowering of the water table (and/or an increase in groundwater/soil salinity) during the drought years.

Our results suggest that developments that revegetate slopes above wetlands as quickly as possible after clearing, or undertake clearing in stages, will minimise effects on water table levels. Pervious detention basins designed to capture runoff and allow infiltration into the soil help replenish aquifers, but also require weed maintenance. This study highlights the significance of maintaining shallow aquifer and catchment processes for the conservation and rehabilitation of coastal wetlands, many of which are listed as Endangered Populations or Endangered Ecological Communities.

***Cunninghamia* (2012) 12(3): 191–211**
doi: 10.7751/cunninghamia.2012.12.016

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## Introduction

Our understanding of groundwater-dependent vegetation in south-eastern Australia, and the potential impacts of urbanization on these ecological communities is generally lacking. Studies examining impacts on groundwater-dependent ecosystems are complicated by rainfall cycles (i.e. dry and wet periods). In Western Australia Groom et al. (2000b) reported that on the Swan Coastal Plain 80 % of trees associated with an aquifer died as a result of rapid water table drawdown, and although the groundwater drawdown was attributed to human causes, below average rainfall resulting in limited water table recharge was a contributing factor. In contrast, in an area of the aquifer where rapid water table drawdown did not occur, no significant decrease in the abundance of overstorey or understorey plant species was detected. A similar study on the effects of long-term groundwater pumping in the United States found that lowering of the water table beneath a deep-rooted plant community reliant on groundwater (phreatophyte), resulted in continuing vegetation change 20 years after the drawdown began (Cooper et al. 2006). Vegetation changes resulting from hydrologic change are difficult to predict because under conditions of a lowered water table, while some species may show significant canopy dieback or death, drought tolerant species may survive with a reduced leaf area for decades, while some species may be able to grow roots to access deeper water tables. Where hydrologic changes are substantial, the whole community may change from one dominated by phreatophytes to one dominated by species with no dependency on the water table (Cooper et al. 2006).

Sand extraction from river beds can impact groundwater-dependent species by lowering the water table. For example in Colorado, Scott et al. (1999) found that sand excavation from the active channel of an ephemeral stream lowered the channel bed by up to 2 m and resulted in sustained declines in crown volume, stem growth and mortality of mature *Populus deltoides* subsp. *monilifera* trees, as well as increased leaf desiccation and branch dieback. Whilst water and sand extraction may lower the water table, catchment urbanization can either increase or decrease water tables, depending on the nature of the development. The proportion of catchment imperviousness and forested area, and the degree of outlet constriction were the most important factors affecting wetland hydroperiod in a study on the impact of urban stormwater on 19 wetlands in Washington State USA (Reinelt et al. 1998).

Some groundwater-dependant vegetation communities tolerate saline conditions. Morris and Collopy (1999) investigated water use and salt accumulation by *Eucalyptus camaldulensis* River Red Gum and *Casuarina cunninghamiana* River Oak on a site with shallow (0.7–3.0 m deep) saline groundwater in northern Victoria. Modelled results indicated that more than half of the water uptake was sourced from groundwater. They also found that soils were slight to moderately saline below 30 cm depth, reaching a maximum salinity at around 200 cm. Soil salinity varied seasonally in response to water table movements. One of the reasons for the decline of riparian vegetation in semi-arid regions of Australia is increased salt accumulation in the soil. In healthy *Eucalyptus largiflorens* Black Box woodlands on the lower River Murray, the trees opportunistically use low-salinity deep soil water, that overlies highly saline groundwater (Holland et al. 2006). In this ecosystem, recharge of the water table occurs by vertical seepage through the soil profile, and horizontal bank recharge from surface water within 50 m of a permanent or ephemeral stream. In a closed canopy swamp forest in South Australia, Mensforth and Walker (1996) showed that *Melaleuca halmaturorum* uses saline groundwater (41 ppt; 0.3–1.2 m deep) in summer and a combination of rainfall and groundwater in winter. An ability to rapidly re-activate dormant roots in response to changes in soil water availability contributes to its survival. Mensforth and Walker (1996) also noted that dilution of stored salt in the unsaturated zone with winter rainfall and the subsequent groundwater rise is a process important to the survival of *Melaleuca halmaturorum* trees.

The rehabilitation of Endangered Ecological Communities (EECs) and Endangered Populations (EPs) is a growing industry but there is little research to support the development of rehabilitation targets and strategies (Hill et al. 2005; Kooyman & Rossetto 2006; Mackenzie & Keith 2009). A small population of *Eucalyptus parramattensis* subsp. *parramattensis* (Parramatta Red Gum) trees on a small area (about 3.7 hectares) near Warnervale, on the Central Coast of New South Wales, has been listed as an Endangered Population (EP) under *the NSW Threatened Species Act*. The *Eucalyptus parramattensis* Woodland grows on a drainage depression adjacent to Porters Creek Wetland, but at the upstream end of the catchment. The habitat of *Eucalyptus parramattensis* is generally considered to be low-lying and often wet sites (Benson & McDougall 1998; Harden 1991). Observations along the Georges River in Sydney and at the current study site in Warnervale by the first author (RP) suggested an association between *Eucalyptus parramattensis* and a shallow water table; evidenced by associated vegetation and water often over the ground surface. From 2002 to mid–2007, the Central Coast of New South Wales (NSW) experienced a significant drought. Observations at Warnervale revealed that a small number of *Eucalyptus parramattensis* trees were under stress, or had died; this was the only species suffering from this condition.

Although part of the Warnervale *Eucalyptus parramattensis* Endangered Population is now in a 1.3 ha reserve managed under a NSW Office of Environment and Heritage (OEH) voluntary conservation agreement, our ability to restore the remainder of the EP back to its original condition may be limited. Prior to its gazettal a proposal for a school on two adjacent land parcels to the north and south of the EP was approved. An arterial road was also subsequently approved. Concerns were raised that if the *Eucalyptus parramattensis* Woodland is dependent on shallow groundwater, construction may alter the groundwater characteristics of the site and negatively affect the EP.

This study examines: (i) the structure and health of the *Eucalyptus parramattensis* population, (ii) whether the population is associated with a shallow aquifer and/or high soil moisture conditions and (iii) whether groundwater or soil moisture conditions were significantly altered during the construction and post-construction stages of an upslope development. This information will allow more informed decisions to be made with respect to managing and rehabilitating groundwater-dependent Endangered Ecological Communities and Endangered Populations.

## Methods

### *Study area*

Porters Creek Wetland is the largest single-bodied freshwater wetland between Sydney and Newcastle, and a major part of its catchment is subject to continuing development. The *Eucalyptus parramattensis* Woodland study area is located in a drainage depression on the eastern edge of the Porters Creek Wetland at Warnervale north of Wyong (Dooralong 1:25 000 mapsheet AMG co-ordinates 56 $^{3}$ 54 9993E, $^{63}$ 20 477N) between the junior and senior schools of the Lakes Grammar School (Figure 1). The drainage depression is underlain by Patonga Claystone (red-brown siltstone and claystone probably deposited on a well-drained, meandering, alluvial floodplain – Uren 1975) and soils of alluvial origin.

The study site covers about 3.7 ha and has two distinctly different areas with different past management histories, a relatively undisturbed Western area, and a more disturbed Eastern area (Figure 2). The Western undisturbed area has well-separated trees of *Eucalyptus parramattensis* as emergents, with a dense midstorey canopy of *Melaleuca nodosa* and occasional *Melaleuca sieberi* giving the impression of a closed canopy (labelled PRG in Figure 1). The understorey is generally sparse or non existent for most of the year, and when ground vegetation does appear, it attracts grazing by the Red-necked Wallaby *Macropus rufogriseus.* Within this sparse ground layer a large orchid population can emerge during August, comprising *Caladenia catenata, Caladenia carnea, Pterostylis nutans, Pterostylis longifolia* and *Thelymitra angustifolia.* Within the more low lying wet area of the mature forest, are pockets of graminoids such as *Gahnia clarkei, Carex appressa, Lepidosperma quadrangulatum* and *Lomandra longifolia.*

The Eastern area appears to have been previously cleared and grazed; the presence of an old dam to the south (Figure

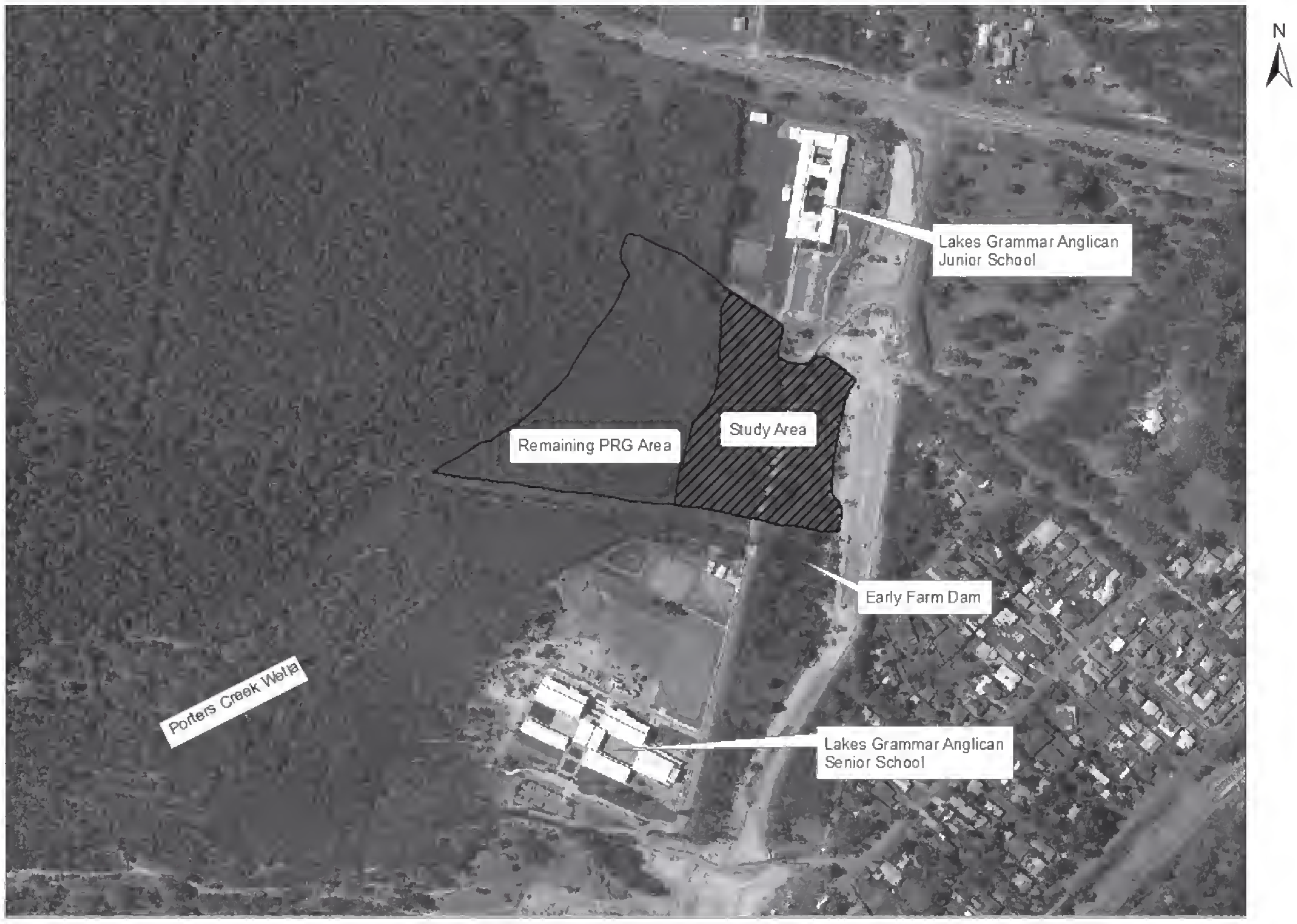

N
Lakes Grammar Anglican Junior School
Remaining PRG Area
Study Area
Early Farm Dam
Porters Creek Wetla
Lakes Grammar Anglican Senior School

**Fig. 1.** Air photo showing Lakes Grammar-an Anglican School in 2011, with the *Eucalyptus parramattensis* Woodland Study Area (hached) between the junior and senior schools. A road divides the Study Area into Western and Eastern sampling areas. Porters Creek Wetland is located to the south-west. The arterial road is under construction to the east. Source: NearMap website.

1) suggests it was farmed, but use of the area had stopped many years before this study started. In contrast to the mature Western woodland, this area supports pockets of immature trees of *Eucalyptus parramattensis* together with occasional trees of *Eucalyptus robusta* (Swamp Mahogany), *Eucalyptus tereticornis* (Forest Red Gum) and *Angophora costata* (Sydney Red Gum). Regenerating midstorey trees of the same species are also present. The groundcover is dense and includes native grasses such as *Imperata cylindrica var. major* Blady Grass, but is dominated by the exotic grasses, *Andropogon virginicus*, *Pennisetum clandestinum* and *Axonopus affinis* (Figure 2).

Downstream of the *Eucalyptus parramattensis* Woodland the vegetation merges into *Eucalyptus tereticornis* Forest with dense *Gahnia clarkei* sedgeland understorey. Further downstream, the vegetation comprises a mosaic of vegetation types such as Low Forest dominated by *Eucalyptus robusta*, Low Forest/Forest dominated by *Melaleuca quinquenervia* and *Casuarina glauca*, Low Swamp Forest dominated by *Angophora costata, Angophora floribunda, Eucalyptus tereticornis, Eucalyptus longifolia* and *Eucalyptus robusta* and Closed Heath Ti-tree Scrub dominated by *Melaleuca ericifolia* (see vegetation mapping by Payne & Duncan 1999; Bell 2002).

The drainage depression supported a population of just in excess of 100 *Eucalyptus parramattensis* trees between 2003 and 2008 within the study area and extending about 80 m to the west of the study area onto private property. However, there is now very little *Eucalyptus parramattensis* left outside these areas as the new road was constructed during 2009 and 2010 (see Figure 1).

Patonga Claystone geology also outcrops south of the study area, on a slope that once supported a mixed Spotted Gum – Ironbark Forest dominated by *Corymbia maculata*, *Eucalyptus fibrosa* and *Eucalyptus siderophloia*, *Eucalyptus globoidea*, *Corymbia gummifera* and *Angophora costata*, with a mid dense sub-canopy of *Melaleuca nodosa* and *Melaleuca sieberi* (Figure 4). This spotted gum forest was harvested from time to time for mine pit props but has now all been cleared for the senior school (Figure 4).

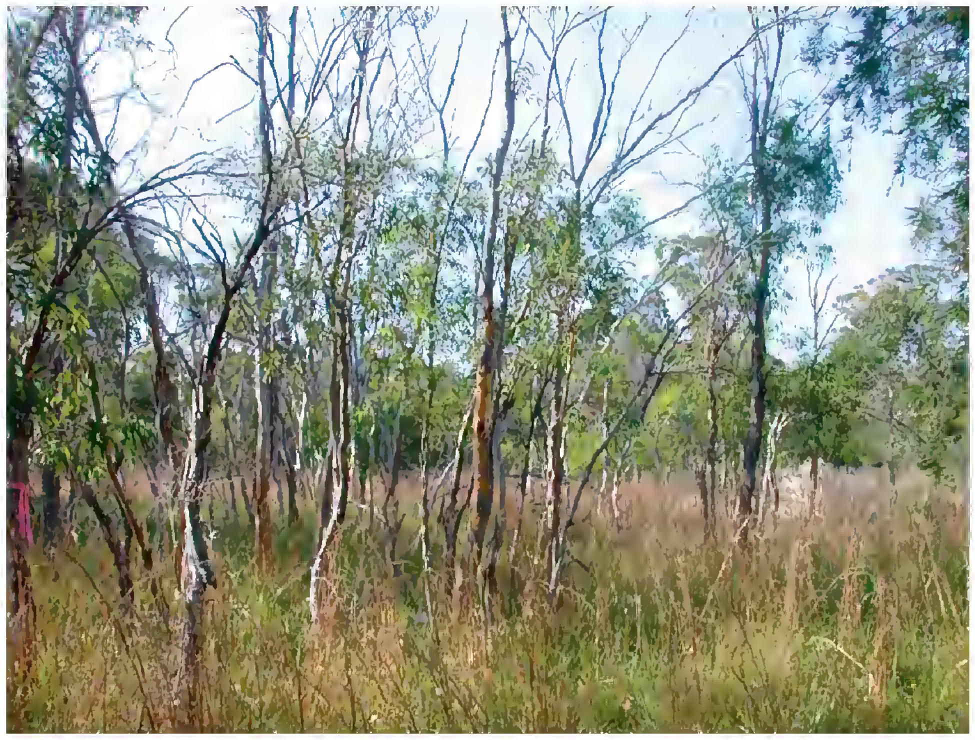


**Fig. 2.** Regrowth *Eucalyptus parramattensis* Woodland in the disturbed Eastern area, showing dense exotic grass cover of *Andropogon virginicus* and tree dieback in July 2003.

### *Tree condition*

Tree condition was assessed in September 2003 (during the drought) and again at the end of the project in July 2011. Nine trees in the Western area and ten trees in the Eastern areas were randomly selected and condition assessed using the method of Groom et al. (2000b), where 1= 1–25% foliage loss; 2= 26–50% foliage loss; and 3= 51–100 foliage loss. The same trees were not necessarily assessed at the two sampling times because many of the original labels had disappeared and a number of the selected trees had been removed as a result of construction of the new internal and arterial road. Therefore, trees that were still labeled were re-measured and others were selected from the few that remained.

### *Vegetation sampling*

As the study area is only small (about 3 ha) and the vegetation uniform, one 50 m x 50 m plot was set out in

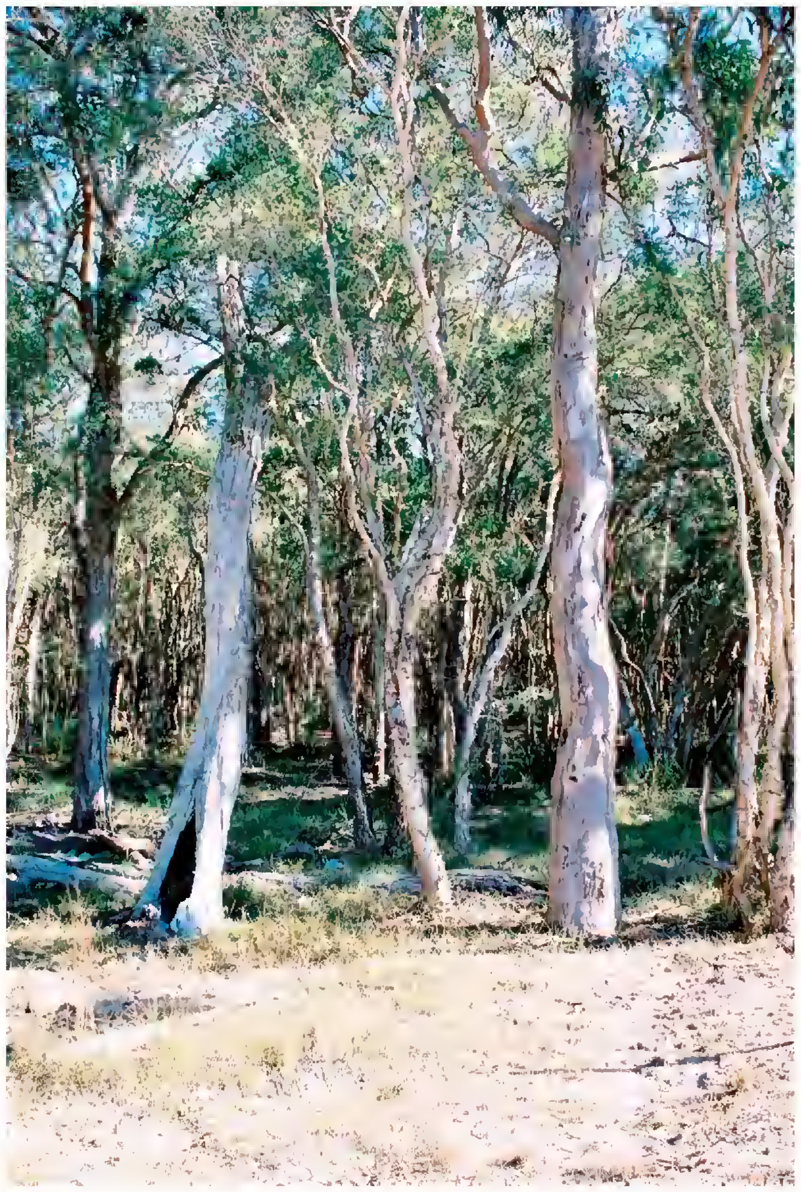


**Fig. 3.** Mature *Eucalyptus parramattensis* Woodland in the undisturbed Western area, showing the *Melaleuca sieberi* and *Melaleuca nodosa* sub-canopy and the sparse ground vegetation cover in July 2003.

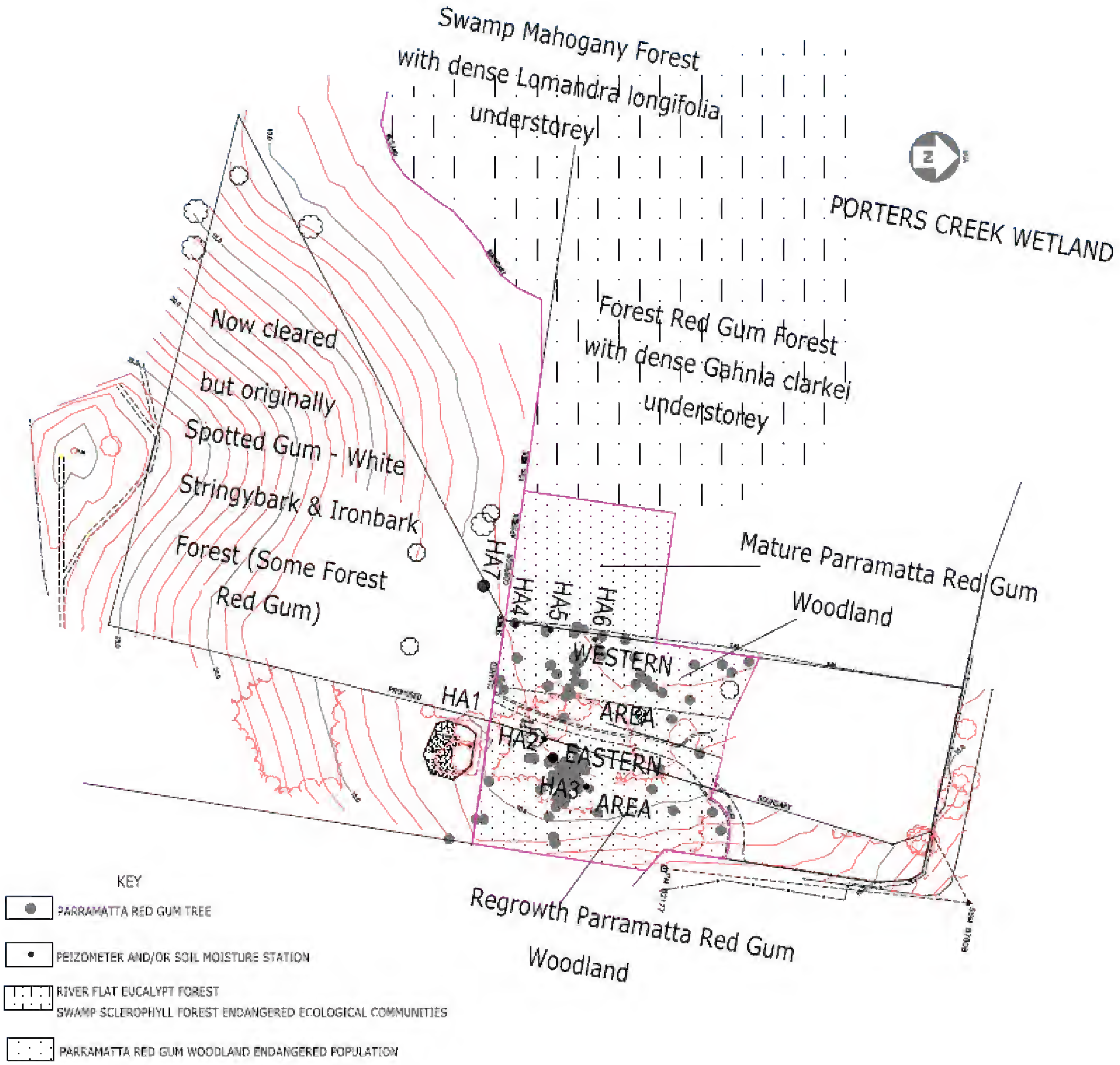

Swamp Mahogany Forest
with dense Lomandra longifolia
understorey
PORTERS CREEK WETLAND
N
Forest Red Gum Forest
with dense Gahnia clarkei
understorey
Now cleared
but originally
Spotted Gum - White
Stringybark & Ironbark
Forest (Some Forest
Red Gum)
Mature Parramatta Red Gum
Woodland
HA7
HA4
HA5
HA6
WESTERN
AREA
HA1
HA2
EASTERN
HA3
AREA
Regrowth Parramatta Red Gum
Woodland
KEY
● PARRAMATTA RED GUM TREE
• PEIZOMETER AND/OR SOIL MOISTURE STATION
RIVER FLAT EUCALYPT FOREST
SWAMP SCLEROPHYLL FOREST ENDANGERED ECOLOGICAL COMMUNITIES
PARRAMATTA RED GUM WOODLAND ENDANGERED POPULATION

**Fig. 4.** The study area at Warnervale showing the location of *Eucalyptus parramattensis* trees in grey. Piezometer locations (HA1-HA3) are shown along a 200 m gradient. To the south the Spotted Gum- White Stringybark- Ironbark Forest on a Patonga Claystone slope has now been cleared. (Original base plan prepared by Trehy, Ingold & Neate Surveyors, 2002 and amended 2012.)

each of the eastern and western areas and all trees with a diameter at breast height (dbh) > 10 cm were measured and the species recorded. For the overall canopy tree composition, basal area was measured and stand importance values (SIV) were calculated by averaging the relative density and relative dominance data for each tree species. Tree size class histograms were prepared. Further vegetation sampling using three randomly selected 20 m x 20 m plots was undertaken using the standard procedure of HCCREMS, which at that time used a 1–6 Braun Blanquet scale for cover abundance scores for each species recorded in the quadrat. This information provided a plant species list for this vegetation community.

### *Soil and groundwater investigation*

Piezometers were located at the upstream edge of the drainage depression and across the tributary to establish whether changes in water table depth and gradient occurred between the pre-, during-construction and post-construction stages of development. Pre-construction (Stage 1) monitoring began in December 2004 and finished in March 2006. During this time the Junior School was built but this was downslope of the *Eucalyptus parramattensis* and had no impact on the water table. Water table measurements were undertaken during this time to obtain the normal undisturbed water table profile. Stage 2, the construction stage (April 2006 to January 2007) involved clearing the Spotted Gum Forest on the southern slope and construction of the Senior School, which is upslope of the *Eucalyptus parramattensis* Woodland. During Stage 2 a second pervious artificial wetland was constructed at the base of the north-eastern facing slope. During the post-development stage, measurements were sporadic as the project was deemed finished. However when some smaller drainage works and an oval were subsequently constructed, water tables were again measured (March 2009–March 2010).

In 2003, before construction commenced, three water table monitoring stations (HA1–HA3) were installed across the drainage depression in the Eastern area (Table 1; Figure 4). In August 2009 HA5 was installed to measure changes in the groundwater depth at a downstream location in the Western area (Table 1; Figure 4). Soil profile characteristics beneath the *Eucalyptus parramattensis* Woodland, as well as depths to the water table and bedrock were recorded during piezometer installation.

Water table depths were measured in the piezometers fortnightly or monthly (February 2003–February 2008 and from April 2009–March 2010). HA5 was monitored from September 2009–March 2010. Groundwater depths were converted to Australian Height Datum (AHD) reduced levels because the top of each piezometer was levelled into a state survey mark (Table 1). Water was extracted at each piezometer by a submersible 12 volt pump. A calibrated Yeo-Kal Model 611 Intelligent Water Quality Analyser was used to measure groundwater salinity. Soil moisture tension was measured at the same locations as the piezometers (HA1–HA3) and at an additional three stations (HA4–HA6) located in the western area. At each station gypsum blocks were inserted into the soil at a depth of 300 mm below the surface. Soil temperature (at the ground surface) and soil moisture tension were measured each fortnight between June 2003 and March 2006.

### *Statistical analyses*

Water table level and soil temperature data were normally distributed. Soil moisture data were not normally distributed and were log transformed, where required. A two-tailed t-test was conducted to determine if there was a significant difference in the mean soil temperature within the regrowth (eastern) and the mature (western) *Eucalyptus parramattensis* Woodland. Spearman correlations were used to determine the relationship between monthly rainfall, soil moisture tension, soil temperature and water table level. As the water table levels in the three piezometers were measured a number of times the effect of the piezometer location (i.e. HA1, HA2, HA3) and the treatment (i.e. pre-, during and after construction) was assessed using repeated measures ANOVA, which was also used to test for differences in groundwater salinity. For these analyses, Levene's test of equality of error variances and Box's test of equality of covariance indicated that the assumptions of homogeneity of error variance and homogeneity of covariance (i.e. compound symmetry) had not been violated (Tabachnick and Fidell 1989). Tests of significance for the repeated measures ANOVA used the more conservative Greenhouse-Geiser and Huynh-Feldt statistics (Tabachnick and Fidell 1989). As monthly rainfall

**Table 1. Location and height data for piezometer (P) and/or soil moisture (SM) stations. AHD = Australian Height Datum.**

| Station | Easting | Northing | Height (m) AHD | Installation Date | Notes |
|---|---|---|---|---|---|
| HA1 | $^{3}$ 54 973.12 | $^{63}$ 20 404.02 | 10.16 | 20.1.2003 | P;SM |
| HA2 | $^{3}$ 55 020.07 | $^{63}$ 20 466.88 | 9.31 | 20.1.2003 | P;SM |
| HA3 | $^{3}$ 55 060.68 | $^{63}$ 20 502.13 | 9.41 | 20.1.2003 | P;SM |
| HA4 | $^{3}$ 54 922.78 | $^{63}$ 20 441.95 | | 20.1.2003 | SM |
| HA5 | $^{3}$ 54 927.18 | $^{63}$ 20 471.20 | 8.76 | 20.1.2003 (SM) 12.8.2009 (P) | P;SM |
| HA6 | $^{3}$ 54 934.68 | $^{63}$ 20 509.76 | | 20.1.2003 | SM |

data was not normally distributed, differences among pre-, during and post-construction rainfall were examined using the non-parametric Kruskal Wallis test. The difference in mean tree condition at the start and end of the study was tested using ANOVA, after substituting the midpoint of each foliage loss class for the condition scale (i.e. 1 = 12% loss; 2 = 38% loss; 3 = 75.5% loss). All analyses were conducted using SPSS version 17.

## Results -Prior to construction

### *Tree condition*

For the *Eucalyptus parramattensis* individuals sampled, there was a lower basal area and lower stem density in the Eastern area compared to the Western area, and size classes were smaller (25–190 mm dbh – Eastern, 70–250 mm dbh – Western) (Table 2; Figure 5), suggesting past removal of trees and some more recent recruitment. Dieback was evident in all *Eucalyptus parramattensis* trees in both the eastern and western areas in early 2003, but tree death was particularly noticeable in the Eastern area (Figure 2). However, this latter observation was not quantified, as dead trees were not selected for the assessment of tree condition (i.e. foliage loss). This perhaps was due to the fact the trees at this location were regrowth.

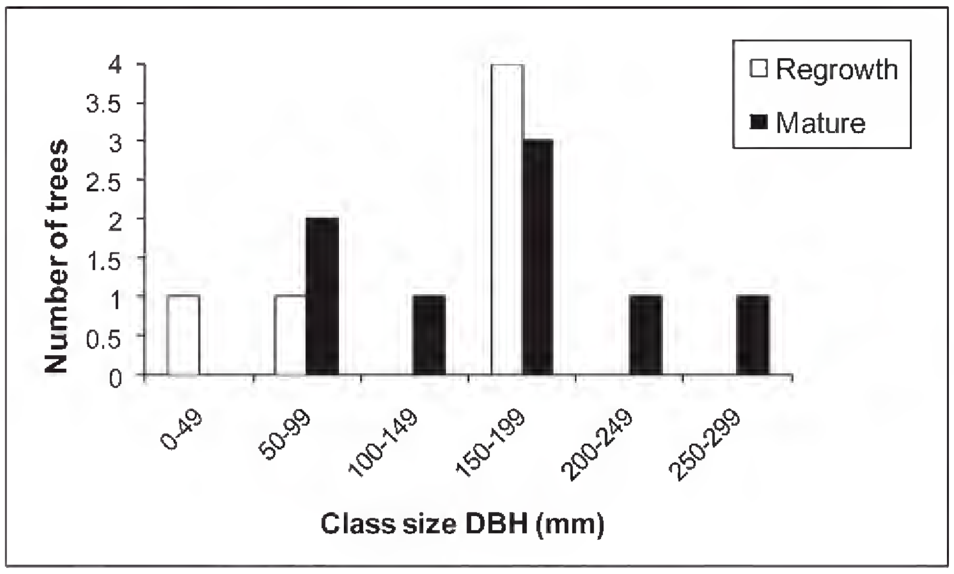


**Fig. 5.** Size class distribution of *Eucalyptus parramattensis* in each of the 50 x 50 m quadrats in the regrowth (eastern) and mature (western) *Eucalyptus parramattensis* Woodland at the Warnervale study area. DBH = diameter at breast height.

### *Vegetation and soils*

Despite having its highest basal area in the Western woodland, *Eucalyptus parramattensis* had a low stand importance value (SIV) in comparison with the *Melaleuca* understory stratum. *Melaleuca nodosa* had the highest SIV in the Western woodland while *Melaleuca sieberi* had the highest SIV in the Eastern woodland (Table 2). The full description of the composition of the *Eucalyptus parramattensis* Woodland is given in Appendix 1.

The sub-surface soil profile below the *Eucalyptus parramattensis* Woodland consisted of plastic clay to depths ranging from 3.35m (at HA3) to the maximum depth of investigation of 4.45 m (at HA1), overlying a fine to coarse grained clayey sand (Figure 6). The contact between the clayey and sandy soils corresponded to a level at about 4 m, just below RL 6 m AHD (the surface is between 9–10 m AHD).

### *Groundwater*

During piezometer installation, groundwater inflows were encountered at 3.5 m depth below the ground surface in HA1, at 2.5 m in HA2 and at 3.1 m in HA3. Each standpipe was bailed dry after installation and the water table allowed to develop over a period of two days. Following this, static water table measurements of 3.12 m, 1.82 m and 1.57 m were recorded at HA1, HA2 and HA3, respectively (giving water table levels of 6.9, 7.18 and 7.63 m AHD) and after a three year period mean water RLs of 6.52m, 7.09m and 7.45m were recorded. The initial groundwater table was found to lie within a lens of sandy clay, confined between the silty

**Table 2. Abundance of woody species recorded within two 50 m x 50 m quadrats within the Eastern (regrowth) and Western (mature) *Eucalyptus parramattensis* woodland at the Warnervale study area. BA = basal area; SIV = stand importance value. Dead stems were not recorded in the SIV survey. Recorded January 2004 for the mature woodland and February 2004 for the regrowth woodland.**

| | | | **Mean BA ($m^2$)** | **Density plants/ha** | **Relative Density (%)** | **Relative Dominance (%)** | **SIV (%)** |
|---|---|---|---|---|---|---|---|
| Eastern (regrowth) | *Angophora floribunda* | canopy | 0.27 | 2 | 0.5 | 1 | 1 |
| | *Eucalyptus parramattensis* | canopy | 0.21 | 12 | 3 | 5 | 4 |
| | *Melaleuca nodosa* | shrub | 0.19 | 76 | 17 | 22 | 19 |
| | *Melaleuca sieberi* | shrub | 0.11 | 354 | 80 | 72 | 76 |
| Western (mature) | *Eucalyptus parramattensis* | canopy | 0.25 | 32 | 4 | 6 | 5 |
| | *Melaleuca nodosa* | shrub | 0.17 | 536 | 59 | 65 | 62 |
| | *Melaleuca sieberi* | shrub | 0.12 | 396 | 37 | 30 | 34 |

clay soil and Patonga Claystone bedrock (Figure 6). This soil layer, in the vicinity of the *Eucalyptus parramattensis* trees, was in the order of 1.9–2.1 m below the ground surface.

Elevation and the depth of the water table below the ground surface varied across the 200 m transect (Figure 6)**.** Elevation of HA1 was greater than HA2 and HA3, while the elevation of HA2 was slightly lower than HA3 (Table 1; Figure 6). The water table was deepest below HA1 and closest to the surface at HA3 (Figure 6). After three years of monitoring the water table gradient beneath the drainage depression was relatively consistent and dipped to the southwest (i.e. sloping from HA3 to HA1). *Eucalyptus parramattensis* trees were growing in greater numbers between piezometers HA2 and HA3, and the results support the view that *Eucalyptus parramattensis* occurs in locations where water table levels are higher (see Figure 4).

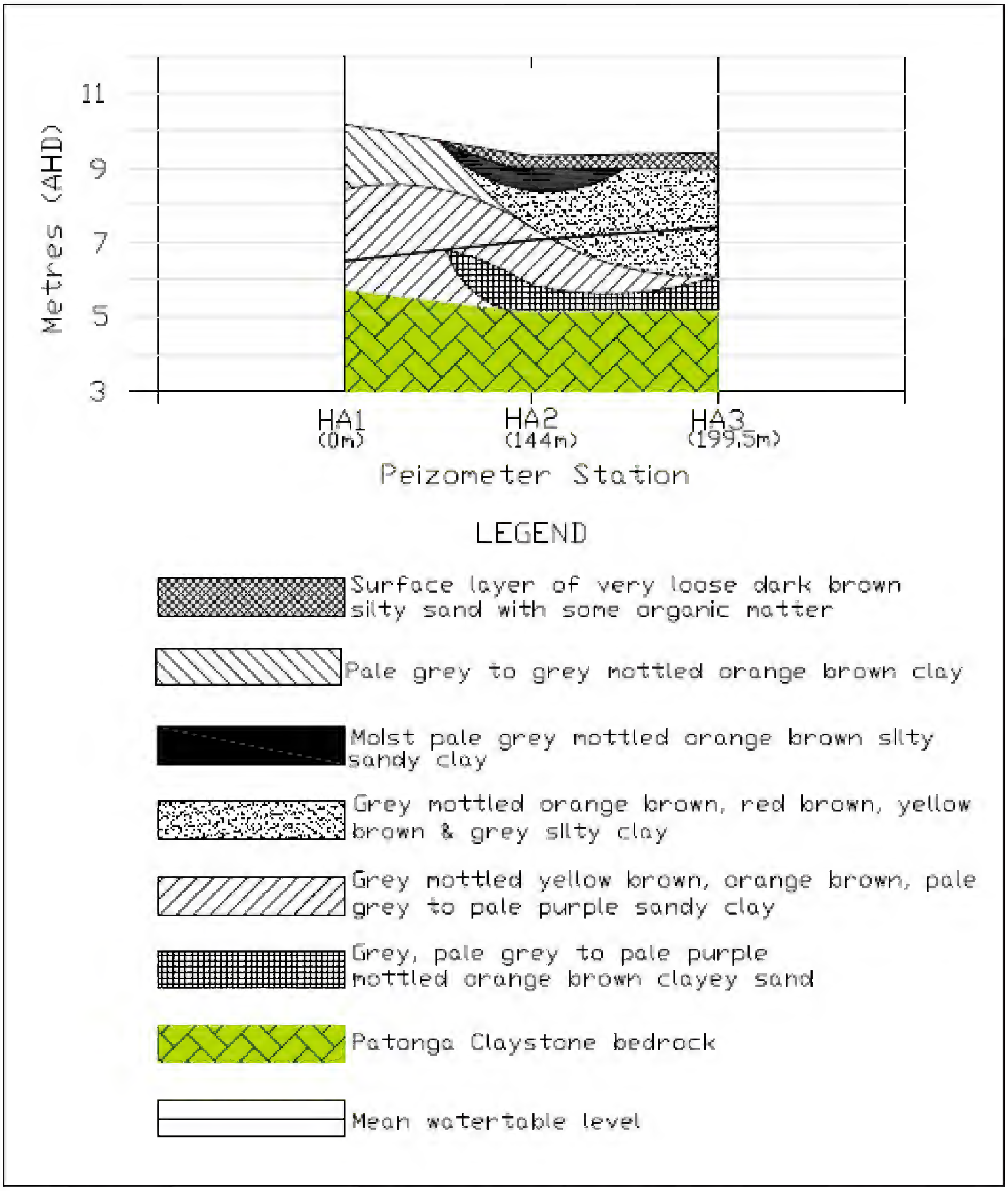
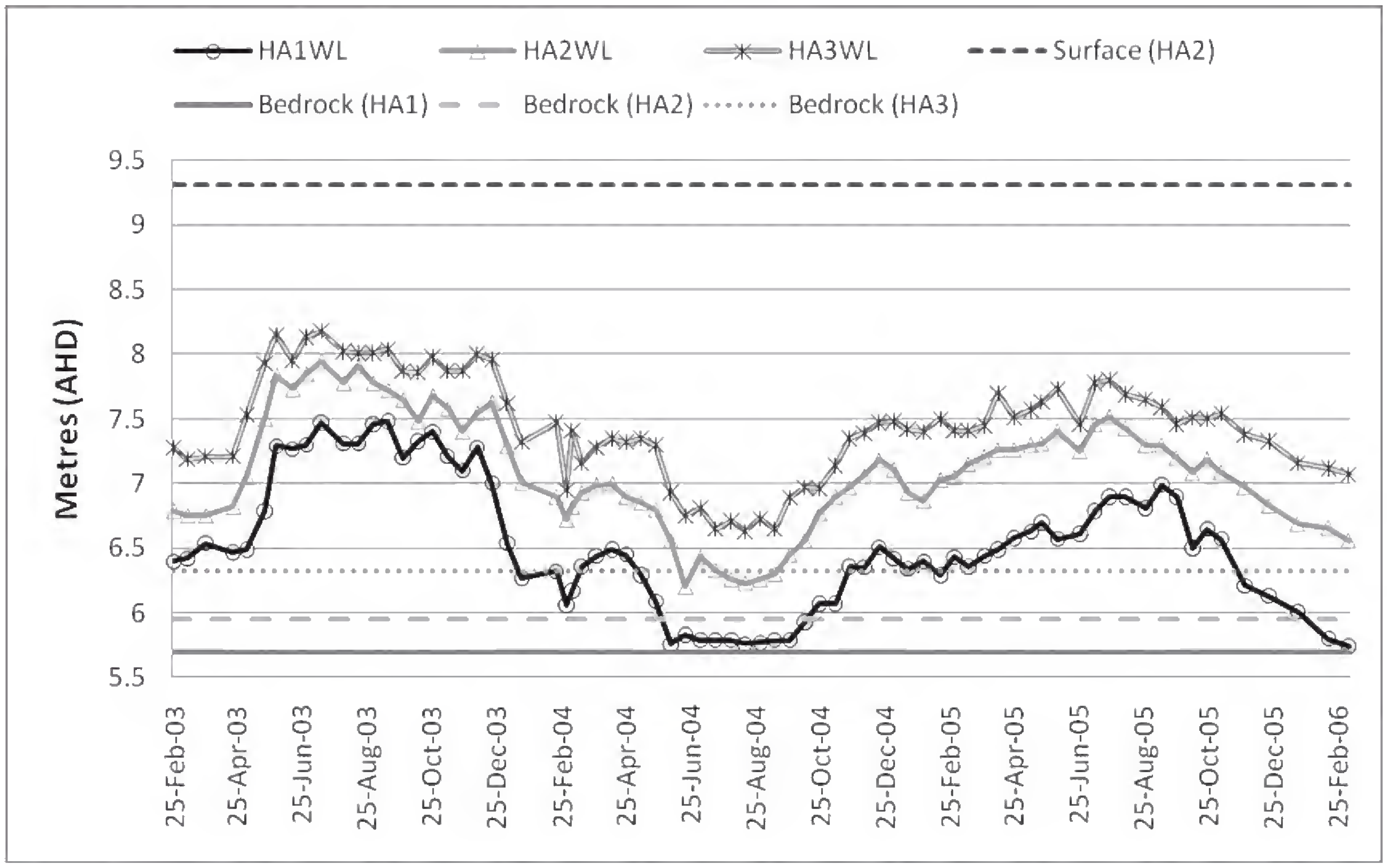

Metres (AHD)
11
9
7
5
3
HA1
(0m)
HA2
(144m)
HA3
(199.5m)
Peizometer Station
LEGEND
Surface layer of very loose dark brown silty sand with some organic matter
Pale grey to grey mottled orange brown clay
Moist pale grey mottled orange brown silty sandy clay
Grey mottled orange brown, red brown, yellow brown & grey silty clay
Grey mottled yellow brown, orange brown, pale grey to pale purple sandy clay
Grey, pale grey to pale purple mottled orange brown clayey sand
Patonga Claystone bedrock
Mean watertable level

**Fig. 6.** Cross-section showing water table and soil profiles within the *Eucalyptus parramattensis* Woodland (eastern area). Information collated from the various borehole logs undertaken during the study by Coffey Geosciences. Locations of the piezometer stations (HA1 – HA3) are shown on Figure 4.

Over the three-year pre-construction period the mean water table level beneath the *Eucalyptus parramattensis* Woodland ranged between 5.7–8.2m AHD (Figure 7) (mean depth below the surface at HA2 was 2.24 m). The water tables rose 0.8–1.0 m during the initial sixth month period up to July 2003 (Figure 7). Rainfall of 681 mm was received between March and July 2003 including a peak of 328 mm in May (records from Wyong Golf Club, 2.8 km south). This rainfall caused a substantial rise in the water table, although there was a time lag (Figure 7). From this time onwards the groundwater gradually dropped to very low levels until no water was recorded in the piezometers. Low water tables were still being recorded in October 2004 (despite 271 mm of rain for that month). These observations indicate that the peak of the drought was between May and September 2004, and that when rainfall events did occur, the rainwater (taking into account losses from evaporation and transpiration) took at least one month to infiltrate through the soil and recharge the aquifer. From October 2004 the water table slowly began to rise towards previous levels peaking in July 2005. After the water tables were drawn down again in February 2006, no water was recorded in the piezometers. Average drawdown rates, during the drier period of the study (February 2003–September 2004), were 0.8 ± 0.1 m over 3 months (Figure 7).

A



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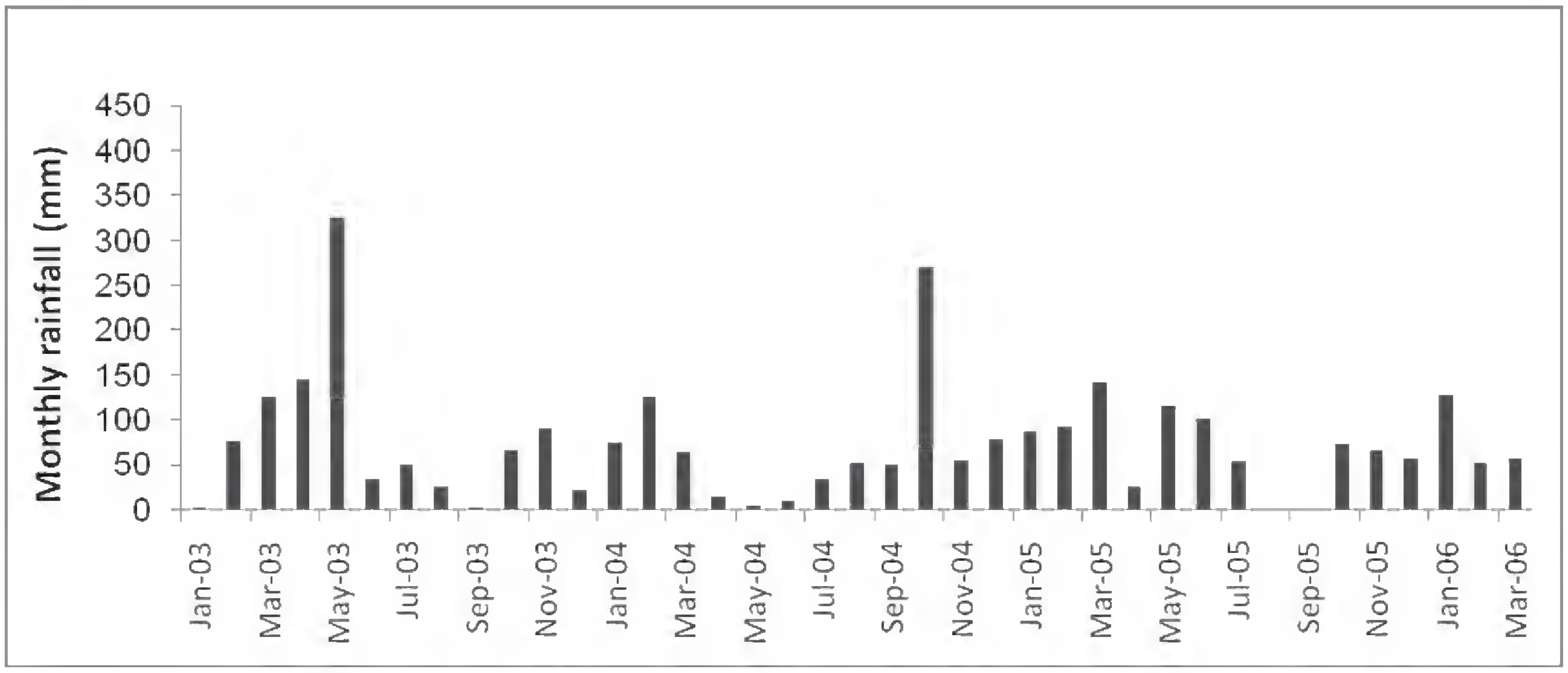


**Fig. 7**. Measured variable prior to construction (a) water table level and bedrock elevations for each piezometer (HA1, HA2 & HA3) and ground surface at HA2; (b) monthly rainfall (Wyong Golf Club). See Figure 4 for the location of the three piezometers within the study area.

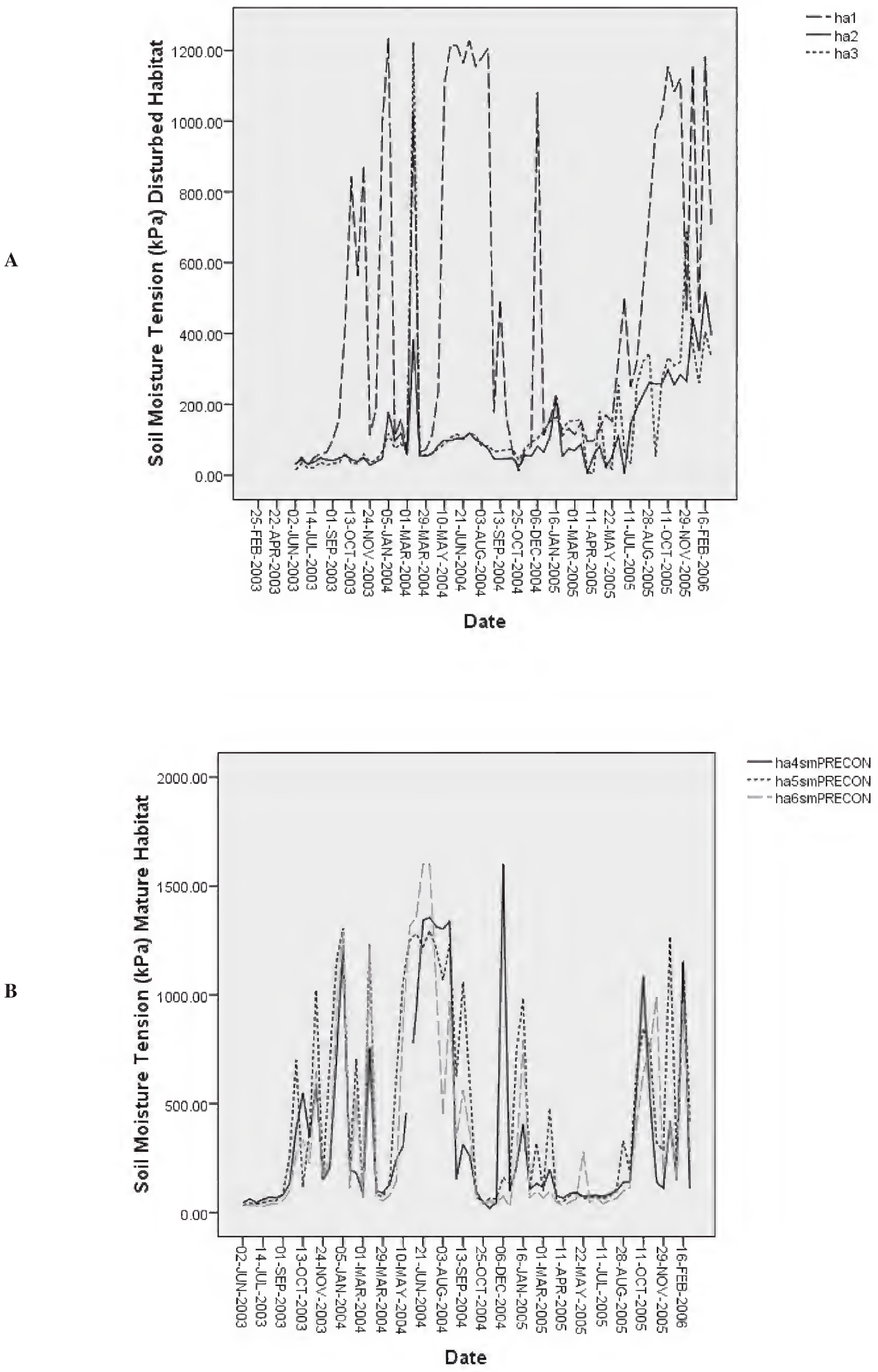


**Fig. 8.** Soil moisture tension in (a) eastern-regrowth and (b) western-mature *Eucalyptus parramattensis* Woodland prior to construction (n = 67). The higher the soil moisture tension value the wetter the soil.

**Table 4. Soil moisture tension (*n* = 67) and soil temperature (*n* = 68) conditions in the mature (western) and regrowth (eastern) *Eucalyptus parramattensis* Woodland prior to construction. See Figure 4 for the location of the soil moisture stations (HA1 – HA6). The higher the soil moisture tension, the wetter the soil.**

| | | **Eastern -Regrowth Forest** | | | **Western-Mature Forest** | | |
|---|---|---|---|---|---|---|---|
| | | **HA1** | **HA2** | **HA3** | **HA4** | **HA5** | **HA6** |
| Soil Moisture (kPa) | Mean (± SE) | 472 ± 54.3 | 119 ± 13.9 | 143 ± 22.3 | 352 ± 51.7 | 453 ± 54.5 | 347 ± 51.3 |
| | Median | 226 | 70 | 78 | 140 | 235 | 114 |
| | Minimum | 11 | 4 | 4 | 21 | 33 | 26 |
| | Maximum | 1234 | 516 | 1223 | 1600 | 1308 | 1600 |
| | Amplitude | 1223 | 512 | 1219 | 1579 | 1275 | 1574 |
| Soil Temperature (°C) | Mean (± SE) | 21 ± 0.6 | 21 ± 0.7 | 21 ± 0.7 | 19 ± 0.6 | 19 ± 0.6 | 19 ± 0.7 |
| | Median | 21 | 21 | 21 | 19 | 19 | 19 |
| | Minimum | 4 | 3 | 6 | 4 | 3 | 3 |
| | Maximum | 33 | 34 | 34 | 31 | 33 | 34 |
| | Amplitude | 28 | 32 | 28 | 27 | 30 | 31 |

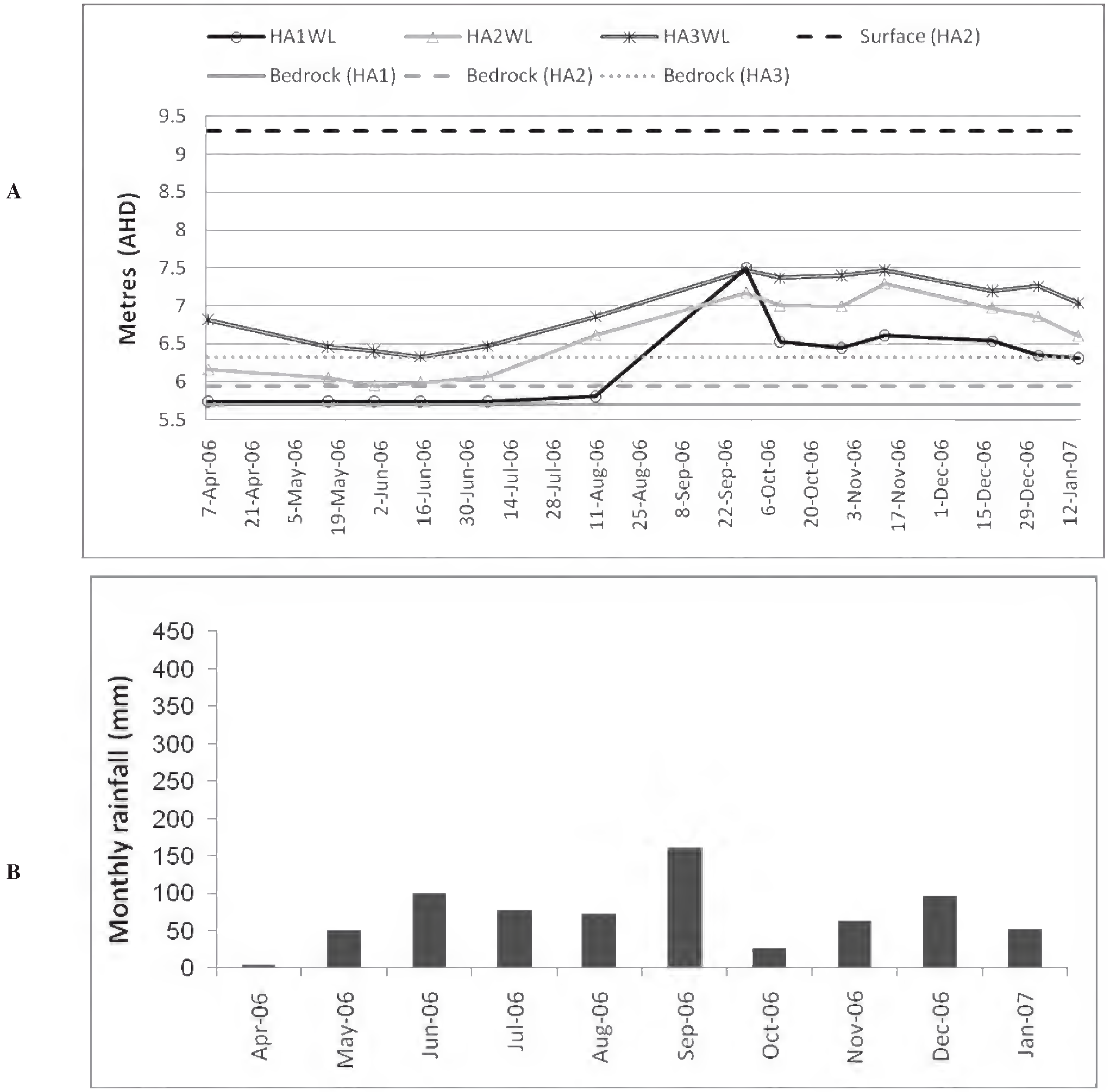


**Fig. 9.** Measured variables during construction (a) water table level and bedrock elevations for each piezometer (HA1, HA2 & HA3) and ground surface at HA2; (b) monthly rainfall (Wyong Golf Club). See Figure 4 for the location of the three piezometers within the study area.

**Table 5: Water table levels beneath the *Eucalyptus parramattensis* regrowth forest prior to, during and after construction. Monthly rainfall data at the closest rainfall station (Wyong Golf Club). n/a – not applicable.**

| | | **Water table (m)** | | | **Rainfall (mm)** |
|---|---|---|---|---|---|
| | | **HA1** | **HA2** | **HA3** | |
| Pre-construction | Mean (± SE) | 6.5 ± 0.06 | 7.1 ± 0.05 | 7.4 ± 0.05 | 75 ± 10.8 |
| (*n* = 74) | Median | 6.5 | 7.1 | 7.5 | 61 |
| | Minimum | 5.7 | 6.2 | 6.6 | 0 |
| | Maximum | 7.5 | 8.0 | 8.2 | 325 |
| | Amplitude | 1.7 | 1.8 | 1.6 | n/a |
| During construction | Mean (± SE) | 6.2 ± 0.14 | 6.6 ± 0.12 | 7.0 ± 0.11 | 71 ± 13.5 |
| (*n* = 13) | Median | 6.3 | 6.6 | 7.0 | 68 |
| | Minimum | 5.7 | 6.0 | 6.3 | 5 |
| | Maximum | 7.5 | 7.3 | 7.5 | 160 |
| | Amplitude | 1.8 | 1.3 | 1.1 | n/a |
| Post-construction | Mean (± SE) | 6.9 ± 0.15 | 7.1 ± 0.13 | 7.3 ± 0.12 | 134 ± 26.6 |
| (*n* = 11) | Median | 7.1 | 6.9 | 7.2 | 115 |
| | Minimum | 6.2 | 6.5 | 6.9 | 19 |
| | Maximum | 7.4 | 7.7 | 7.9 | 397 |
| | Amplitude | 1.2 | 1.2 | 1.0 | n/a |

**Table 6. Mean (± s.e.) percentage foliage loss of *Eucalyptus parramattensis* trees at the Warnervale study site at the start and end of the study period.**

| | **Mean Percentage Foliage Loss** | |
|---|---|---|
| | **September 2003** | **July 2011** |
| Eastern (regrowth) | 32.5 ± 8.1 (10 trees) | 35.4 ± 7.0 (11 trees) |
| Western (mature) | 51.8 ± 8.0 (9 trees) | 30.6 ± 7.6 (11 trees) |

**Table 7. Groundwater salinity levels (ppt) recorded beneath the regrowth (eastern) and mature (western) *Eucalyptus parramattensis* Woodland (in 2009 during the post-construction period ) (n = 8). Means with different subscripts indicate that differences are significant at the p < 0.05 level.**

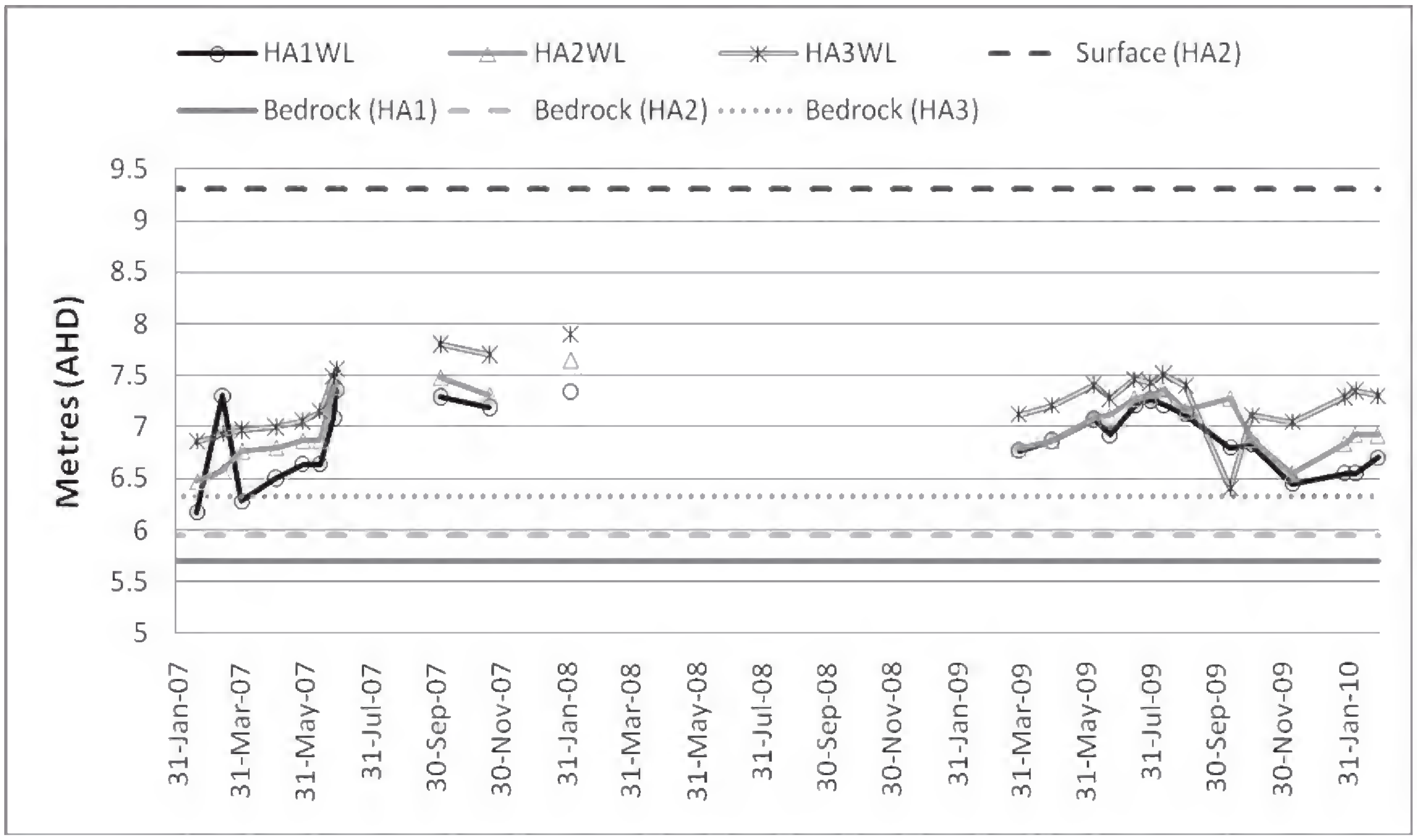
| **Date** | **Regrowth Eucalyptus parramattensis Woodland** | | | **Mature Eucalyptus parramattensis Woodland** | **Old farm dam** |
|---|---|---|---|---|---|
| | **HA1** | **HA2** | **HA3** | **HA5** | |
| 16.10.09 | 8.5 | 11.3 | 12.4 | 17.9 | 0.05 |
| 26.10.09 | 8.2 | 11.2 | 12.2 | 0.4 | 0.02 |
| 2.11.09 | 7.9 | 10.9 | 12.0 | 2.6 | 0.05 |
| 29.12.09 | 8.6 | 12.4 | 13.4 | 13.4 | 0.07 |
| 14.01.10 | 7.9 | 11.4 | 12.2 | 9.9 | 0.03 |
| 09.02.10 | 8.0 | 11.4 | 12.1 | 0.7 | 0.04 |
| 29.07.10 | 9.6 | 11.6 | 12.0 | 1.3 | 0.11 |
| 08.10.10 | 9.3 | 11.3 | 12.1 | 1.2 | 0.13 |
| Mean ± SE | $8.5 \pm 0.23_{a}$ | $11.4 \pm 0.16_{b}$ | $12.3 \pm 0.16_{c}$ | $5.9 \pm 2.42_{abcd}$ | $0.06 \pm 0.014_{d}$ |

### *Soil Moisture and Temperature*

Higher mean soil moisture tensions were observed within the Western-mature forest (HA4–HA6) and at HA1 (Table 4). On average, soil moisture tension was lowest at two of the stations (HA2 and HA3) within the Eastern-regrowth forest. Mean soil temperature was significantly lower within the western mature forest than the eastern regrowth forest (t = –16.8; d.f. = 4; p < 0.001) (Table 4).

Wetting and drying cycles within the topsoil showed the greatest fluctuations in soil moisture (Stations HA4 to HA6) were in the Western-mature forest where little ground cover vegetation exists (Figure 8b). In the Eastern-regrowth area, wide fluctuations in soil moisture tension were observed at HA1, similar to that within the mature forest, but in contrast to the relatively stable soil moisture tensions recorded at HA2 and HA3 (Figure 8a). The soil profiles indicated that the topsoil at HA1 was clay and similar to that at HA4, HA5 and HA6 , whilst the topsoil at HA2 and HA3 was silty sand (Figure 6). HA1, HA4, HA5 and HA6 probably had soil moisture tensions that are variable because the clay topsoils would hold water more tightly when conditions are dry and water would be slow to infiltrate when conditions are wet. In contrast, HA2 and HA3 probably had more stable soil moisture tensions because the sandy topsoils allows water to infiltrate and drain away relatively quickly.

A



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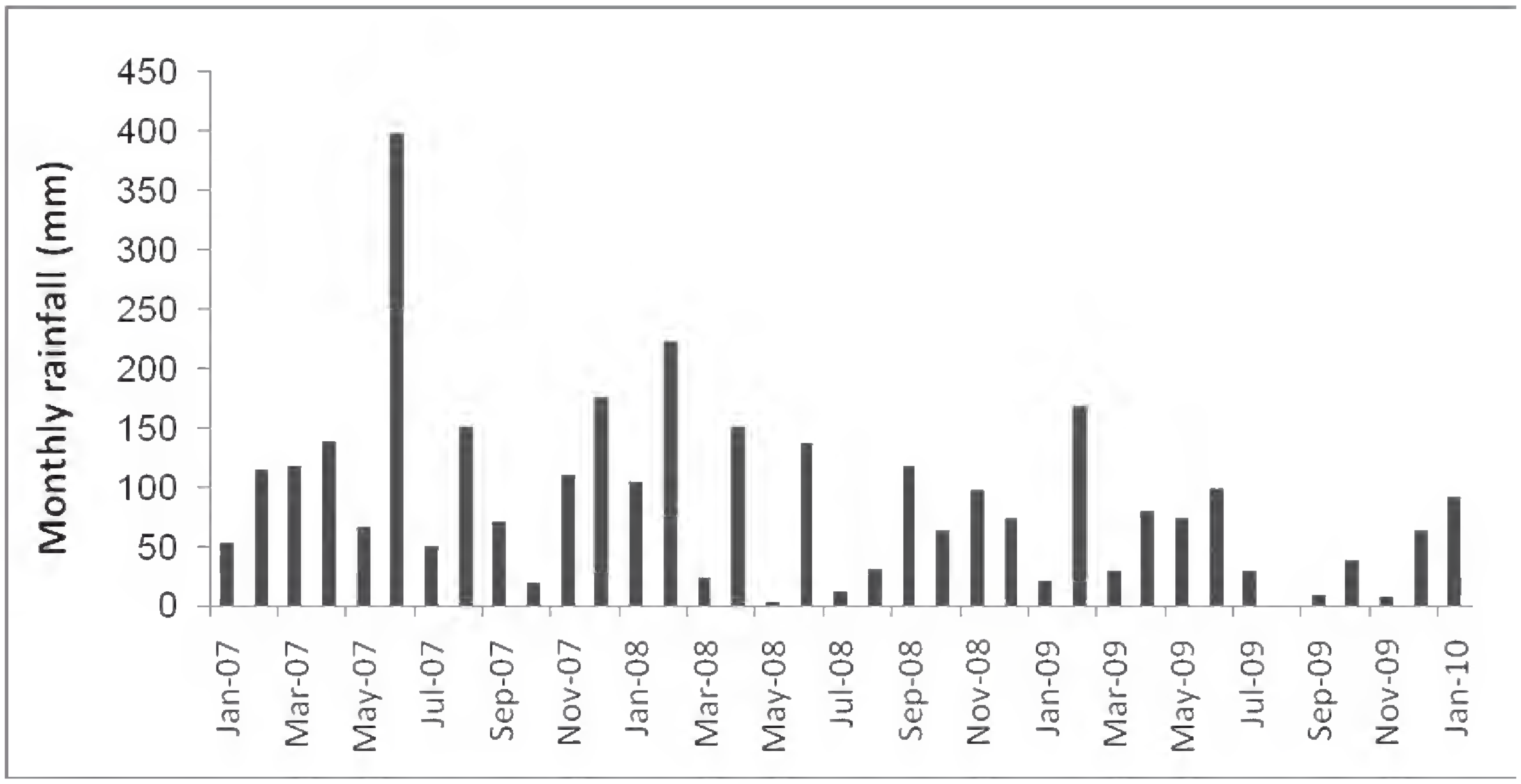

**Fig. 10.** Measured variables after construction (a) water table level and bedrock elevations for each piezometer (HA1, HA2 & HA3) and ground surface at HA2; (b) monthly rainfall (Wyong Golf Club). See Figure 4 for the location of the three piezometers within the study area. Note there is a gap in data recording for the post-construction period.

Significant negative correlations between soil moisture tension and rainfall occurred at HA1 ($r = -0.38$, $p < 0.05$, $n = 61$), HA4 ($r = -0.35$, $p < 0.05$, $n = 61$) and HA5 ($r = -0.40$, $p < 0.05$, $n = 61$). Soil moisture tension and water table level were significantly negatively correlated at the three stations where water tables were monitored (HA1, $r = -0.30$, $p< 0.05$, $n= 67$; HA2, $r = -0.37$, $p< 0.01$, $n= 67$; HA3, $r = -0.38$, $p< 0.01$, $n= 67$).

## Results-During and after construction

### *Water table levels*

During the construction period the water table levels at the three stations in the Eastern-regrowth area were, on average, 0.3–0.5 m lower, and much more variable, than during the pre-construction period (Table 5). Post-construction water table levels, at HA2 and HA3, were similar to pre-construction levels. Repeated measures ANOVA showed that water table levels between the treatments (i.e. pre-, during and post-construction) were significantly different (2 df; $F = 5.7$; $p < 0.01$).

Post hoc Bonferroni tests showed that there was a significant difference between water tables, prior to and during construction (2 df; $p < 0.01$), as well as between water tables during and post-construction (2 df; $p < 0.05$). However, pre- and post-construction water tables were not significantly different (2 df; $p > 0.05$). The amplitude of the water table was greatest during the pre-construction period, most likely due to the variability in rainfall during this period (Table 5; Figure 9). Median monthly rainfall (Table 5) was significantly greater during the post-construction period than during pre-construction (2 df; $\chi^2 = 6.6$, $p < 0.05$).

Repeated measures ANOVA demonstrated that there was a significant difference in water table levels between the piezometer locations (2 df; $F = 634.0$; $p < 0.001$), as well as a significant interaction between piezometer location and treatment (4 df; $F = 22.2$; $p < 0.001$). That is, the effect of construction on the water table was dependent on the location of the piezometer. The nature of this interaction can be seen in the water table response to the 160 mm rainfall event in September 2006; where the rise and fall of the water table at HA1, was much greater than at stations HA2 and HA3 (Figure 9). During large rainfall events, the north-eastern facing slope without any vegetation cover caused more runoff to flow to the base of the slope, and the ponding of surface water at HA1 (i.e. the piezometer station closest to the base of the slope) resulted in the water table rising above the levels of HA2 and HA3. Such events altered the normal (i.e. dipping to the south-west) water table gradient beneath the *Eucalyptus parramattensis* Woodland (Figure 9). This trend during high rainfall events continued after construction (e.g. March 2007), but only while the grass cover on the slope was being established (Figure 10). Following the establishment of the grass cover, the water table gradient re-stabilised to pre-construction levels (Figure 10; Table 5).

### *Tree condition*

In 2003, the mean percentage foliage loss indicated that the trees in the Western-mature area were in a poorer condition than those in the Eastern-regrowth area (Table 6). In May 2009 those trees that could be found with their original tags were reprouting via epicormic shoots; one of the tagged trees in the western area had died. By July 2011 the condition of the trees in the Western-mature area (in terms of foliage loss) had improved; the condition of the trees in the Eastern-regrowth area remained the same. However, ANOVA showed that there was no significant difference in mean percentage foliage loss between the eastern and the western areas (1 df; $F = 0.37$; $p = 0.65$), nor between the two time periods (1 df; $F = 0.58$; $p = 0.58$) and there was no interaction between time and location.

### *Groundwater Salinity*

Groundwater salinity was only measured in 2009 (post-construction), and was consistently 8–12 ppt in the Eastern-regrowth area, ranged from 0.6–18 ppt in the Western-mature area, and was insignificant in the water in the adjacent farm dam (see Figure 1 for location) (Table 7). Repeated measures ANOVA demonstrated that there was a significant difference (4 df; $F = 21.0$; $p < 0.01$) in groundwater salinity among the five locations examined (Table 7) but Post hoc Bonferroni tests showed that the only significant differences in salinity between locations were those involving comparisons with HA5 (Table 7). This was due to the extreme variability in salinity recorded at HA5, suggesting that the seal between the PVC pipe and the surrounding soil was poor and surface water was entering the piezometer.

Mean (± SE) water table levels (AHD reduced levels) during the period of salinity measurements were 6.8 ± 0.40 m at HA1, 7.0 ± 0.41 m at HA2, 7.3 ± 0.41 at HA3 and 6.8 ± 0.88 m at HA5. The higher variability in water table levels at HA5 is also consistent with surface water entering the piezometer. As most of the readings in Table 7 were taken after rain, the low salinity levels sometimes recorded at HA5 may be explained by the fresh surface water inputs sitting on top of the more saline groundwater. An additional sample taken during drier conditions (February 2011) recorded salinity levels at HA1 and HA2 of a similar order to those shown in Table 7, whilst salinity recorded at HA3 and HA5 were 3.1 ppt and 2.1 ppt, respectively.

## Discussion

### *Vegetation, soils and water table depth*

At Warnervale *Eucalyptus parramattensis* trees occur at sites associated with clay soils derived from Patonga Claystone where there is a high water table, within 1.4 m of the surface, but where the water table can drop to as deep as 3.1 m during droughts (i.e. pre-construction levels at HA2). It has been shown throughout this study that water levels in the Porters Creek aquifer increase after rainfall events (with a lag period) and decrease when rainfall is low. These results are consistent with those gathered from the Swan Coastal Plain in Western Australia where water levels consistently increase after recharge from winter rainfall (with a lag period) and decrease during the dry summer period (e.g. Groom et al. 2000). At the Porters Creek aquifer the level of drawdown is substantial, with groundwater levels at HA1 being at bedrock level (4.5 m below the surface) between May & September 2004, when groundwater levels at HA2 & HA3 were also low (2.9 m and 2.7 m respectively below the surface) (see Fig. 7).

Analyses of historical rainfall data for the NSW Central Coast (Erskine & Townley-Jones 2009) show significant multi-decadal periods of high rainfall (1863–1900, 1949–1990) alternating with low rainfall (1901–1948, 1991–2008). Although the underlying meterological causes are unclear, El Niño-Southern Oscillation events and/or Interdecadal Pacific Oscillation (IPO) phases are possibly involved (Erskine & Townley-Jones 2009). Analysis of rainfall data from Wyong Golf Club shows that the low annual rainfall experienced during 1991–2008 was not significantly different to that experienced during 1901–1984. That is, mean annual rainfall at Wyong during these two drier periods was similar and was 200–300 mm lower than during the high rainfall periods of 1885–1900 and 1949–1990 (Erskine & Townley-Jones 2009). Thus, any long-lived phreatophytic plants at our study site have experienced episodes of limited access to groundwater similar to that found in the current study and would have some capacity to survive these periods (e.g. by using available soil moisture or tolerating water stress). It is possible that the population of *Eucalyptus parramattensis* has survived previous episodes of canopy dieback; it was obvious from the regular visits that the ground understorey vegetation was only present during wetter periods.

The subcanopy of the Western-mature *Eucalyptus parramattensis* Woodland which was located in the lowest areas (i.e. 8–9 m AHD) with clay topsoils, is dominated by *Melaleuca nodosa*, while *Melaleuca sieberi* dominated the slightly higher elevation of the Eastern regrowth forest (i.e. 9.3–9.4 m AHD) where the topsoil was sandier. The association of *Melaleuca nodosa* with a shallow water table is consistent with Griffith et al. (2004) who showed that the roots of *Melaleuca nodosa* seedlings planted in dry heath had reached the water table (1–1.5 m below the surface) after 6 months of growth. There appears to be no information on the root depth of *Eucalyptus parramattensis*. However a NSW north coast study shows the roots of heathland plants (0.25–1 m high) can access water table depths greater than 7 m (Griffith et al. 2008); in south-western Western Australia the roots of *Banksia ilicifola* can reach depths of 9 m (Groom 2004). These findings suggest that the aquifer identified in this study is likely to be within the reach of *Eucalyptus parramattensis* roots, and other shrubs at the site (e.g. *Melaleuca nodosa*). Thus, according to the guidelines of Eamus et al. (2006b) the *Eucalyptus parramattensis* woodland at the study site is an example of a groundwater-dependent ecosystem because of the subsurface presence of groundwater and the likelihood that the roots of the canopy plant species can access the water table and capillary fringe.

Groundwater-dependent vegetation is susceptible to the rate and season of drawdown (Eamus & Froend 2006). During a relatively dry period the *Eucalyptus parramattensis* population in this study experienced water table drawdown rates of 0.27 m per month, a rapid drawdown rate compared, for example, to that observed during the same period by Chalmers et al. (2009) in a shallow (~ 2 m deep) alluvial aquifer immediately adjacent to Widden Brook (Upper Hunter, NSW). Substantial rainfall (> 600 mm over a four month period) was shown to replenish the water table in the current study by about 1 m. Recharge of the groundwater after large rainfall events (> 250 mm in a month) could take up to a month when prior conditions had been relatively dry.

The canopy dieback evident in *Eucalyptus parramattensis* individuals at the start of the study in 2003 may be due to a number of causes. Some eucalypts survive drought by stomatal control (i.e. reducing transpiration), while others grow extensive and deep root systems to reach water unavailable to other plants (Bell & Williams 1997). Some drought-tolerant eucalypts have been shown to accumulate high concentrations of solutes in tissues (osmotic adjustment) to maintain turgor, or have vessel elements (narrow and thick-walled) that allow them to tolerate low water potentials without cavitation (Bell & Williams 1997). Additional strategies phreatophytic species may use to avoid water deficits include the ability for root growth to keep pace within declining water tables (Gurnell et al. 2001), root patterns that enable the use of more than one type of water resource (Mensforth & Walker 1996; O'Grady et al. 2002; Groom 2004) and the redistribution of groundwater or deep soil moisture by hydraulic lift (Groom 2004). Thus, the failure of any of these mechanisms may be responsible for the canopy dieback in *Eucalyptus parramattensis* and further work would be required to determine the primary cause(s). By the end of the study some of the *Eucalyptus parramattensis* individuals showed signs of recovery, producing epicormic shoots to replace foliage lost before the study commenced. Although it is likely that this recovery is linked to the rise in the maximum depth of the water table at the end of the drought, it should be noted that the water table level when foliage was lost is unknown and the trees may also be responding to increased soil water availability from higher rainfall during the post-construction period.

The lack of any significant differences in the mean percentage foliage loss of the *Eucalyptus parramattensis* individuals sampled at the start and the end of the study may be a consequence of the small sample size, the loss of tags and that the foliage loss classes used were too broad to be useful. The methods of Stone and Haywood (2006), which also involves estimating the proportion of the current tree crown which is of epicormic origin, should be considered for future studies. Other improvements would be to examine long-term plant response to water stress by measuring population vigour, and short-term responses by measuring leaf water potential or stomatal conductance (Eamus et al. 2006). Further, the current study could not determine the extent to which *Eucalyptus parramattensis* is dependent on groundwater or how this use changes as groundwater availability varies. Studies similar to O'Grady et al. (2001) and Groom (2004), where sources and patterns of water use are determined by measuring stable isotopes of hydrogen ($^{2}$H) or oxygen ($^{18}$O) and leaf or shoot water-potentials are needed.

### *Groundwater salinity*

According to Lothian and Williams (1988) the boundary between 'fresh' and 'saline' water is imprecise and definitions vary according to need (e.g. an ecologist's definition will differ from a manager of water for human consumption). Ecologists working on inland wetlands in South Australia define fresh as < 3 ppt, slightly saline as 3–10 ppt, saline as 10–100 ppt and highly saline as > 100 ppt (Lothian & Williams 1988). Based on this definition, the groundwater beneath the *Eucalyptus parramattensis* Woodland ranged from slightly-saline to saline. The aquifer associated with Patonga Claystone becomes unconfined north-east of the Wyong River and, consistent with our results, is "generally considered to be low yielding, with moderate to high salinity levels" (Molloy et al. 2009, p. 8). This contrasts with the fresh groundwater (< 0.35 ppt) recorded beneath a floodplain supporting *Casuarina cunninghamiana* forest adjacent to Widden Brook (Chalmers et al. 2012), and in a coastal aquifer below Wallum communities of northern NSW (Griffith et al. 2008). The order of magnitude difference in groundwater salinity levels between the current study and that of Griffith et al. suggests that species that the two studies have in common (e.g. *Melaleuca nodosa* and *Melaleuca sieberi*) have a wide tolerance of groundwater salinity.

In this study salinity was only measured during a relatively wet period, and as we could expect groundwater salinity to have been higher (i.e. saline) during the past drought, there must have been long periods during drought when saline water was the main source of moisture. Some freshwater plants can tolerate salinities as high as 20 ppt (Lothian & Williams 1988) but in areas such as the Chowilla floodplain in South Australia, where riparian communities (particularly *Eucalyptus camaldulensis*) are suffering severe declines in health, the salinity of the shallow (< 5 m) groundwater typically ranges from 22–54 ppt (Overton et al. 2006). The relative contribution of water stress or salinity to the poor tree health of *Eucalyptus parramattensi* observed in the current study cannot be determined from our data.

The salinity and declining tree health on the Chowilla floodplain is driven by a lack of flooding and rising saline groundwater tables resulting from river regulation (Overton et al. 2006). *Eucalyptus largiflorens* Black Box has been shown to be reliant on moderately saline (< 26 ppt) groundwater, but where salinity exceeds 26 ppt on the floodplains of the River Murray it opportunistically uses low-salinity deep soil water, together with other water sources such as rainfall (Holland et al. 2006). The low-salinity deep soil water is recharged vertically by rainfall (and floodwaters) or horizontally by bank recharge from the River Murray or ephemeral creeks (Holland et al. 2006). Infiltration of floodwaters and rainfall to the water table occurs through preferential flow paths in clayey soils (e.g. tree-root channels, cracks in clay & topographic depressions) and by diffuse flow in sandy soils where the clay is absent at the break of slope (Holland et al. 2006). Recharge through infiltration of rainfall and water flowing through the narrow drainage depression may be important in lowering the salinity of soil water and groundwater underlying the *Eucalyptus parramattensis* Woodland. Considering that the topsoil at HA1 was clayey and that of HA2 and HA3 was sandier, the lower average salinity at HA1 suggests some kind of preferential flow path within the vicinity of this piezometer (which was located at the break of the slope). Nevertheless, areas with sandy soils (such as those in the vicinity of HA2 and HA3) would be expected to be important for infiltration of rainfall into the water table.

### *Vegetation and soil moisture*

The significant correlation between water table depth and soil moisture suggests that at times the capillary fringe above the water table extends to 30 cm below the ground surface. The relationship between soil moisture tension and water table level is consistent with Groom et al. (2000a), who found that on the deep sands of the Swan Coastal Plain "groundwater levels are closely tied to rainfall events, which in turn, are directly related to soil moisture levels" (p. 81). Significant correlations between rainfall and soil moisture at HA1, HA4 and HA5, where the topsoils are clays were observed. Soil water availability was, on average, higher but more variable where the soils were clay; the locations of which correspond with the semi-cleared upslope position of HA1 and the stations within the mature woodland (HA4, HA5 and HA6). In contrast, the soil moisture availability in the eastern portion of the regrowth area (HA2 and HA3) was, on average, lower but less variable, due to the sandier topsoils.

Opportunistic water-use strategies have been demonstrated for a number of Australian tree and shrub genera (i.e. *Eucalyptus, Melaleuca, Acacia, Banksia* – Overton et al. 2006) growing in environments that experience periodic water deficits. The ability of *Melaleuca halmaturorum* to rapidly re-activate dormant roots at the depth where water is available is proposed as a mechanism to allow opportunistic use of different water sources (Mensforth & Walker 1996) and it is likely that *Eucalyptus parramattensis* would also opportunistically use whatever source of water was available. The use of stable isotopes of water and water-potential techniques is needed to confirm this.

The density of *Eucalyptus parramattensis* trees was lower, and a number of individuals had died in the Eastern-regrowth area, where the topsoil is sandier and soil moisture generally lower. Where the topsoil is sandier the trees may rely on the water table to a greater degree and therefore may be more susceptible to water table declines during drought. However, clearing and grazing previously occurred in the eastern area confounding our results and we cannot determine if the latter habitat is more marginal for the species or not.

### *Effect of construction on the water table*

The water table gradient found beneath the *Eucalyptus parramattensis* Woodland had an inverse relationship to the surface level. During and after disturbance on the adjacent slope (stage 2 construction), one piezometer (HA1) showed peak water table levels after large rainfall events over and above the levels further down slope (i.e. HA2 and HA3). This caused the water table gradient to alter, although no corresponding impact on the health of *Eucalyptus parramattensis* trees was detected. The reversal of the water table gradient can be explained by the clearing of slope vegetation and the increased runoff accumulating at the base of the slope. This effect continued whilst the slope was being revegetated, but once the grass cover was well established the water table gradient re-stabilised back to pre-construction levels. Pre- and post-construction mean water table depths were not significantly different from each other, but the fact that median monthly rainfall was significantly greater during the post-construction compared to pre-construction period confounds the results. For this reason, the study would have benefited from having a control site where water tables could be monitored in the absence of upslope clearing. Unfortunately in the case of this endangered population, finding a comparable control site was not possible.

Our findings are consistent with those observed by Jutras et al. (2006) in a study of water table changes following pre-commercial thinning of forested wetlands in Quebec in that the water table was affected in the first year, but hydrologic recovery occurred in the second year. Jutras et al. (2006) found that faster recovery on particular sites was related to an increase in ground cover which, with its higher interception rate, caused the water table depth to reach pre-treatment levels. However their findings differed from ours in that the mean water table levels rose (by 2 cm) after tree removal, rather than declined. This discrepancy can be explained by the differences between the two studies. Their study involved canopy tree removal from a forested wetland, which reduced evapo-transpiration and caused a corresponding rise in the water table; the degree of the water table rise was related to the amount of basal area removed (Jutras et al. 2006). Our study involved not only the removal of canopy trees but an increase in impervious surfaces on a slope, above a wetland. Thus, any reduction in evapo-transpiration on the slope will not increase the water table if this is counteracted by impervious surfaces directing at least some of the increased runoff away from the wetland area via stormwater drains.

### *Implications for management*

The findings of this study are applicable to other areas where groundwater-dependant Endangered Ecological Communities and Populations occur adjacent to upslope development. To minimize alteration of the water table, adjoining slopes need to be revegetated as quickly as possible after clearing, or clearing should be undertaken in stages. No impact on the health of the *Eucalyptus parramattensis* trees was observed to result from the short-term change to the water table. Whilst this finding is consistent with Griffith et al. (2008), who found that dry heath species could tolerate waterlogging for up to 3 months, the period of possible waterlogging in the current study was very brief (HA1 > HA2 for less than a month in Fig. 9). It should be noted that consistent waterlogging resulting from runoff directly flowing from adjacent impervious surfaces (e.g. isolated individuals retained in a carpark) can cause severe dieback in this tree species. While *Eucalyptus parramattensis* trees have a high requirement for soil moisture and may rely on shallow aquifers, like most woody species they cannot tolerate prolonged waterlogging and its tolerance of waterlogging may be less than that found in Swamp Sclerophyll Forest vegetation communities (Payne pers. obs.).

Given that the current study confirmed that a shallow aquifer is present below *Eucalyptus parramattensis* Woodland and the study area is at the upstream end of the catchment, it is likely that the aquifer is fed by the surrounding slopes to the north-east. Thus, management of runoff within the catchment is essential. Rather than allow surface runoff from the slopes to be diverted away from the aquifer underlying the *Eucalyptus parramattensis* Woodland (through road and stormwater drains associated with the development) a more conservative approach was adopted as part of this development. Pervious detention basins were constructed which captured the overland runoff (and fines of the Patonga Claystone soils) and allowed water to infiltrate and replenish the aquifer. Due to the clayey nature of the soils, runoff collected in the basins infiltrates slowly into the aquifer. Such basins, though economical to construct, require a high level of maintenance and over three years they became very weedy, which has implications for infecting adjoining sensitive vegetation communities. After seven years, and with management, a more natural community has developed.

Where Patonga Claystone soils are present, impervious constructed wetlands, whose function is to capture overland runoff, and treat the water through both its longer storage time and the uptake of nutrients by wetland plants, do not always achieve the desired results. Patonga Claystone soils are highly prone to erosion because of their low shear strength and slaking prone behaviour (Nunt-jaruwong, 2006), leading to high levels of turbidity. Measurements taken during rainfall and settling events in an impervious basin near, and at, the study site showed turbidity levels beyond the scale of the measuring instrument (the shallow muddy water meant that a representative sample to determine total suspended solids (TSS) was not possible). There is now a requirement that total suspended solids levels be below 50 mg/l, prior to discharge through adjoining wetland ecosystems (Wyong Shire Council, pers. com.). However for this soil type, settlement of the fines below 50 mg/l is never achieved naturally and flocculation methods using alum-based polymers may not achieve the required turbidity levels (even after several attempts), and can result in aluminium levels many times the Australian Standard within the discharge water from the basin. Where such circumstances occur, the potential impacts on aquatic fauna within wetland vegetation communities need to be considered.

Whilst the water table was observed to re-stablise to pre-construction levels in this study, broad-scale clearing and increases in impervious surfaces within the catchment may have a cumulative effect on the hydrologic regime. Although broadscale clearing of habitats may have an economic and social basis, the environmental cost needs to be acknowledged because many habitats bordering wetlands have Endangered Ecological Communities and Populations. The impact of urban development on coastal floodplain wetlands is complicated further if the groundwater upon which some species depend is saline (as in this study). Similar to floodplains in the drier parts of Australia, rainfall and floodwater infiltration may play a crucial role in maintaining groundwater salinities and soil water at levels that the existing vegetation can tolerate. Developments that impede this recharge may add to the multiple stresses (natural and human induced) already experienced by these vegetation communities. Long-term monitoring of the groundwater underlying coastal woody wetlands will be required if we are to adequately understand the impacts of urban development, drought and the possible risk posed by climate change on the health and recruitment of wetland Endangered Populations such as *Eucalyptus parramattensis* Woodland.

## Conclusion

The *Eucalyptus parramattensis* Endangered Population at Warnervale occurs on a narrow drainage depression above a shallow slightly-saline to saline groundwater aquifer (8–12 ppt; 1.4–3.1 m deep). A water table gradient was found beneath the *Eucalyptus parramattensis* Woodland which had an inverse relationship to the surface level. Most *Eucalyptus parramattensis* trees occur where the water table is higher. A study using stable isotopes of water and water-potential techniques is needed to determine the extent to which *Eucalyptus parramattensis* uses groundwater and soil water sources.

Although in the initial stages of the study (2003) some *Eucalyptus parramattensis* trees died, no further impact on the trees was found and most trees are now in the state of recovery (2012). It is likely that the poor health of *Eucalyptus parramattensis*, which initiated this study, was due to water stress from a lowering water table (and/or an increase in groundwater/soil salinity) during drought. Trees at slightly higher elevations or on sandier soils may be expected to suffer greater stress.

Land-clearing for an upslope development significantly decreased the average water table level below the *Eucalyptus parramattensis* Woodland during the construction phase. Peaks also occurred at the base of the slope after large rainfall events, having the effect of reversing the direction of the water table gradient. However, the hydrology appeared to re-stabilise to pre-construction levels once the upslope area had been landscaped and revegetated with grass. Whilst this construction event did not show any impacts on the health of *Eucalyptus parramattensis* trees within the woodland, isolated trees retained within the development (and surrounded by impervious surfaces) suffered dieback illustrating that the species cannot tolerate continuous waterlogging.

Soil mapping is recommended around groundwater-dependant ecosystems likely to be impacted by development projects. Soil type determines where runoff water can be captured, held and allowed to infiltrate efficiently back into the aquifer, and consideration of soil maps prior to the construction of pervious detention basins will help ensure that maximum environmental benefits are achieved.

Further investigations of water table and groundwater salinity fluctuations in coastal wetlands is warranted, particularly in areas where climate change predictions suggest a risk of increased drought severity and/or rising groundwater associated with sea level rise. As climatic cycles occur on the scale of decades (Erskine & Warner 1988), monitoring to determine the cumulative effects of land-clearing, and increased, within catchment, impervious surfaces on groundwater-dependant Endangered Ecological Communities and Populations will need to be long-term (especially where unimpacted control sites are unavailable).

## Acknowledgements

The Lakes Grammar – an Anglican School provided funds for the aquifer investigation. We thank Jenny Evans, Howard Townsend and Tristan Stevenson whom guided the project over the many years. Coffey Geosciences installed the piezometers and provided the soil logs. Trehy, Ingold & Neate and Clarke Dowdle & Associates prepared all survey information. We also thank Sharyn Styman of Wyong Shire Council for providing data on floodplain mapping, Robyn Meldrum and Boris Branwhite who helped in the field, Wayne Erskine for helpful feedback on an early version of the manuscript and Michael Somerville for preparation of Figure 1. The constructive feedback provided by two reviewers is gratefully acknowledged.

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Manuscript accepted 2 April 2012

## Appendix 1

### Vegetation descriptions of *Eucalyptus parramattensis* Woodland for a)Western and b)Eastern sites at Warnervale (recorded October 2003).

a) Western – mature area

Open Woodland: *Eucalyptus parramattensis* subsp. *parramattensis*

Structure: Open woodland with a low closed forest beneath

Habitat: Alluvium overlying Patonga Claystone at depth on upper reaches of coastal freshwater swamps

Distribution: Porters Creek north of Wyong NSW

Floristic Composition: Isolated emergent trees of *Eucalyptus parramattensis subsp. parramattensis* project above the main canopy. A low closed forest forms the sub-canopy dominated by *Melaleuca nodosa, Melaleuca sieberi* and *Melaleuca linariifolia*. Understorey cover is generally sparse but in moister areas is dominated by *Gahnia clarkei, Lepidosperma quadrangulatum* and *Carex appressa.*

Related mapping units: Incorporated into MU26 Narrabeen Alluvial Drainage Line Complex of Bell (2004) and *Eucalyptus parramattensis /Melaleuca sieberi*/Swamp Mahogany swamp forest on the Central Coast of Somerville (2009)

b) Eastern – regrowth area

Open Woodland: *Eucalyptus parramattensis* subsp. *parramattensis*

Structure: Open woodland with a dense grassy understorey

Habitat: Alluvium overlying Patonga Claystone at depth on upper reaches of coastal freshwater swamps

Distribution: Porters Creek north of Wyong NSW

Floristic Composition: Isolated emergent trees of *Eucalyptus longifolia* occasionally occur. Either a low open regenerating woodland or a low forest is present dominated by *Eucalyptus robusta, E. parramattensis subsp. parramattensis, E. amplifolia, Angophora floribunda, Melaleuca nodosa* and *M. sieberi* are present. A further regenerating low open woodland layer of *M. nodosa, E. parramattensis subsp parramattensis* is often present.. The ground understorey grass cover is always dense and dominated by *Andropogon virginicus, Briza minor, Briza maxima* and *Axonopus affinis.*

Related mapping units: Incorporated into MU26 Narrabeen Alluvial Drainage Line Complex of Bell (2004) and *Eucalyptus parramattensis /Melaleuca sieberi*/Swamp Mahogany swamp forest on the Central Coast of Somerville (2009)

## Appendix 2 a) Native plant species and b) Exotic species recorded from *Eucalyptus parramattensis* Woodland at Warnervale (October 2003), 2 plots in western (mature) woodland and 1 plot in eastern (regrowth) woodland.

| a) Native species | Family | Frequency 3 plots |
|---|---|---|
| *Acacia longifolia* subsp. *longifolia* | Fabaceae | 2 |
| *Angophora floribunda* | Myrtaceae | 2 |
| *Carex appressa* | Cyperaceae | 1 |
| *Carex brunnea* | Cyperaceae | 1 |
| *Casuarina glauca* | Casuarinaceae | 1 |
| *Cynodon dactylon* | Poaceae | 2 |
| *Cyperus difformis* | Cyperaceae | 2 |
| *Dianella caerulea* var. *producta* | Phormiaceae | 1 |
| *Dianella longifolia* | Phormiaceae | 1 |
| *Drosera auriculata* | Droseraceae | 1 |
| *Entolasia stricta* | Poaceae | 1 |
| *Eragrostis* sp. | Poaceae | 3 |
| *Eucalyptus amplifolia* | Myrtaceae | 1 |
| *Eucalyptus longifolia* | Myrtaceae | 1 |
| *Eucalyptus parramattensis* subsp. *parramattensis* | Myrtaceae | 3 |
| *Eucalyptus robusta* | Myrtaceae | 2 |
| *Festuca spp.* | Poaceae | 2 |
| *Gahnia clarkei* | Cyperaceae | 1 |
| *Gonocarpus micranthus* subsp. *micranthus* | Haloragaceae | 2 |
| *Gonocarpus tetragynus* | Haloragaceae | 2 |
| *Hydrocotyle peduncularis* | Apiaceae | 3 |
| *Imperata cylindrica* var. *major* | Poaceae | 1 |
| *Juncus planifolius* | Juncaceae | 2 |
| *Juncus usitatus* | Juncaceae | 3 |
| *Lomandra longifolia* | Lomandraceae | 2 |
| *Melaleuca linariifolia* | Myrtaceae | 1 |
| *Melaleuca nodosa* | Myrtaceae | 3 |
| *Melaleuca sieberi* | Myrtaceae | 3 |
| *Microlaena stipoides* | Poaceae | 2 |
| *Microtis parviflora* | Orchidaceae | 1 |
| *Opercularia varia* | Rubiaceae | 1 |
| *Oxalis chnoodes* | Oxalidaceae | 2 |
| *Oxalis* sp. | Oxalidaceae | 2 |
| *Philydrum lanuginosum* | Philydraceae | 2 |
| *Pratia purpurascens* | Lobeliaceae | 2 |
| *Ranunculus inundatus* | Ranunculaceae | 3 |
| *Ranunculus lappaceus* | Ranunculaceae | 2 |
| *Schoenus* sp. | Cyperaceae | 1 |
| *Viola betonicifolia* | Violaceae | 1 |
| *Viola hederacea* | Violaceae | 1 |
| *Woollsia pungens* | Epacridaceae | 1 |

| b) Exotic species | Family | Frequency 3 plots |
|---|---|---|
| *Andropogon virginicus* | Poaceae | 3 |
| *Asphodelus spp.* | Asphodelaceae | 1 |
| *Axonopus fissifolius* | Poaceae | 3 |
| *Briza maxima* | Poaceae | 2 |
| *Briza minor* | Poaceae | 3 |
| *Cerastium glomeratum* | Caryophyllaceae | 2 |
| *Conyza* sp. | Asteraceae | 3 |
| *Cyperus eragrostis* | Cyperaceae | 2 |
| *Hypochaeris radicata* | Asteraceae | 3 |
| *Paspalum urvillei* | Poaceae | 2 |
| *Persicaria strigosa* | Polygonaceae | 2 |
| *Plantago lanceolata* | Plantaginaceae | 2 |
| *Rubus fruticosus* sp. agg. | Rosaceae | 1 |
| *Rumex crispus* | Polygonaceae | 1 |
| *Senecio madagascariensis* | Asteraceae | 3 |
| *Stenotaphrum secundatum* | Poaceae | 2 |
| *Trifolium dubium* | Fabaceae | 2 |
| *Vulpia bromoides* | Poaceae | 2 |

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Date of Publication:
30/07/2012

Cunninghamia
A journal of plant ecology for eastern Australia

The Royal
Botanic Gardens
& Domain Trust

ISSN 0727-9620 (print) • ISSN 2200-405X (Online)

# The pre-colonial distribution of grasslands, woodlands and forests on the Werribee plains, Victoria

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***Abstract*****:** We use historic plans and recent field observations to reconstruct and describe the former (pre-1750) character and distribution of vegetation on the Werribee Plains, near Melbourne. The primary outcome of this research is a detailed vegetation map. The ecological factors controlling the distribution of trees and open-plains are also discussed. The results show that most of the area was treeless grassland at the time of European settlement (1835). This grassland was broken up by clearly-defined areas of Eucalypt forest, some of which remain. There is, in contrast, little remaining trace of the woodlands of *Allocasuarina* and *Banksia*, which we show were once widespread on the plains and stony rises beyond the Eucalypt forest. This work is timely, given the proposal for the creation of two large new reserves in the area, which contain many areas that may be subject to restoration.

Keywords**:** pre-1750, she-oak, sheoke, fire, grassland, pre-settlement vegetation, anthropogenic

***Cunninghamia*** **(2012) 12(3): 213–227**
doi: 10.7751/cunninghamia.2012.12.017

## Introduction

Natural grasslands and sparsely-treed grassy woodlands once occurred widely in lowland Victoria (Willis 1964, Lunt 1991). Such areas were particularly attractive for graziers, and their distribution influenced the pattern and sequence of European settlement in Victoria during the 1830s and onwards (Batman 1835, Powell 1970, Moloney *et al*. 2006, Boyce 2011). A long history (now over 175 years) of agricultural use has altered these environments, making ecologically intact examples very rare in Victoria, and many of their resident species threatened. Consequently, they are now important for biological conservation. 'Natural Temperate Grassland of the Victorian Volcanic Plain' is now listed as a 'critically endangered' ecological community under the Commonwealth Government *Environment Protection and Biodiversity Conservation Act* 1999 (EPBC Act). Lowland grasslands have suffered similar declines around the world and their conservation is a global challenge (Lunt 1991, Watkinson and Ormerod 2001).

Our understanding of these grassy systems is incomplete. Although we have long understood aspects of their ecology and biological composition (e.g. Sutton 1916–17, Patton 1935, Willis 1964, Stuwe and Parsons 1977, Lunt 1991, Morgan and Lunt 1999), we still lack basic historic information on where grassy systems were located in parts of Victoria. Several recent studies have identified previously unknown or forgotten natural grassland areas, using the historical record or careful analysis of existing vegetation (Cook and Yugovic 2003, Yugovic and Mitchell 2006, Sinclair 2008, McDougall 2008).

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The plains to the immediate west of Melbourne (variously and imprecisely identified as the ‘Keilor’ or ‘Werribee’ Plains) are among the best-studied grassland areas in Victoria (e.g. Sutton 1916–7, Geraghty 1971, McDougall 1987, Growth Areas Authority 2010a–d.). They are part of the story of Melbourne’s settlement (Moloney *et al*. 2006, Boyce 2011) and we know from published accounts that vast expanses of this area were treeless at the time of colonisation. For example, Grimes (1803) described the Werribee area from the coast as “grassy plains to the mountains. No trees.” John Batman (1835) described “Open plains, as far as the eye can see”.

The basic form of the open grassland region of the Werribee Plains is fairly well-known (McDougall 1987), however, the fine detail of vegetation patterns are not well understood. Even the ostensibly treeless plains were apparently not completely treeless. Relict trees of several species still exist in scattered places and many of the early accounts mention pockets of woodland or forest. These fine details of grassland, woodland and forest distribution on the Werribee Plains have gained new interest since the Victorian government proposed the establishment of two large (15,000 ha total) grassland reserves between Melton and Little River (Department of Planning and Community Development 2009, Department of Sustainability and Environment 2009a, Figure 1).

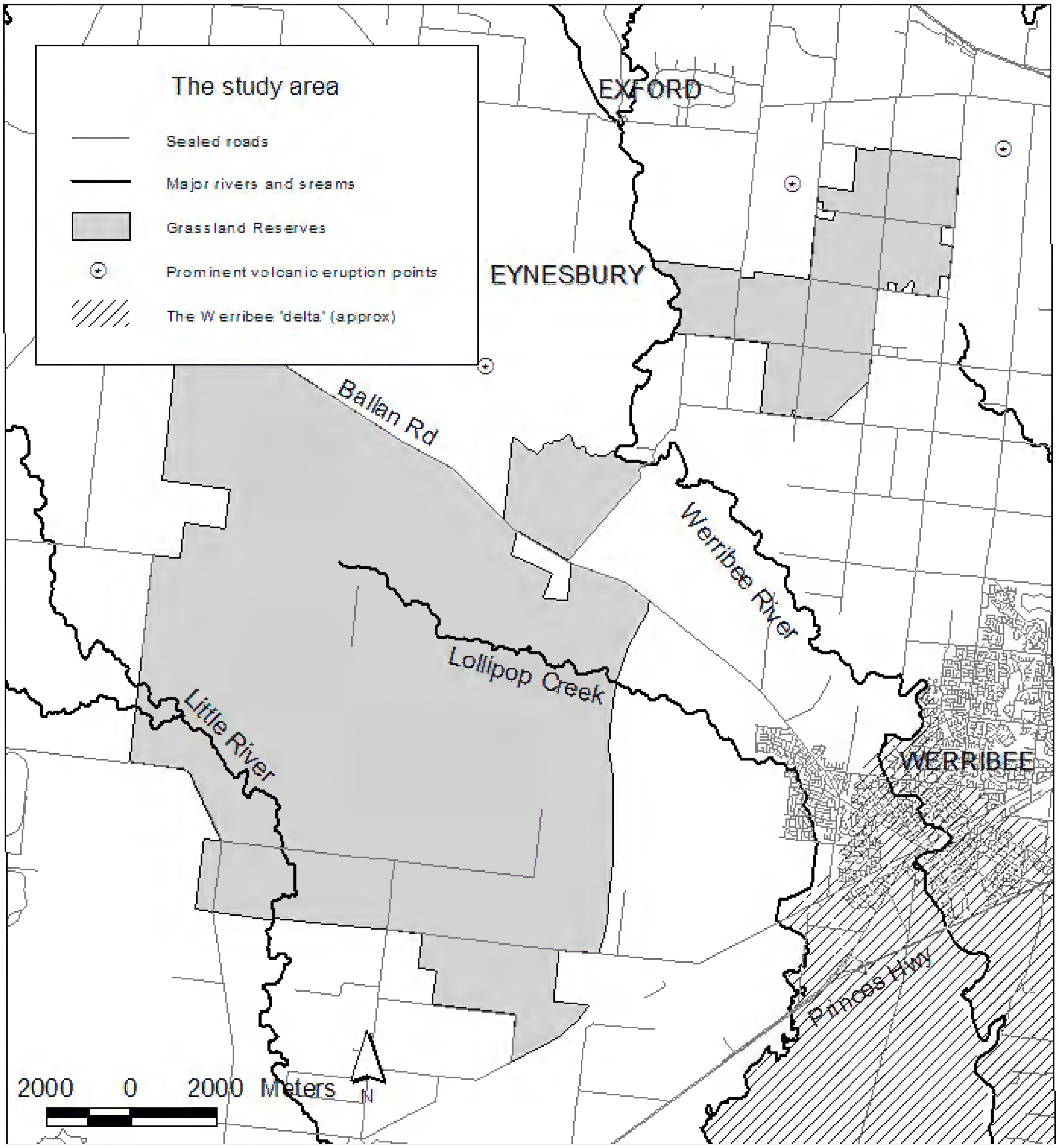

**Fig. 1.** The Werribee Plains study area west of Melbourne.

The reserves contain expanses of land that are degraded, and may be subject to restoration. Most restoration efforts try to emulate or re-create what the relevant ecosystem was like before it was degraded (Higgs 1997). In Victoria this involves understanding the character of the vegetation as it was before the abrupt changes caused by the arrival of agriculture in the1830s. Large scale restoration projects –particularly those involving community groups– often include the planting of trees or shrubs; as their establishment produces visible and appealing landscape-scale changes within a few years. Tree planting may, however, be a threat to the ecological integrity of grasslands (Lunt 1991, Baker-Gabb 2002). It is important to re-establish woody vegetation in appropriate location and quantity. The available pre-colonial mapping of the Werribee Plains is not detailed enough to guide restoration; although some resources are excellent for their intended purposes (e.g. McDougall 1987). Our study aimed to produce a pre-colonial vegetation map with sufficient resolution to guide restoration with (or without) woody species. It is the most detailed to date, and uses a broad range of historic and contemporary data sources.

## Study area

The study area was defined arbitrarily around the proposed grassland reserves, being large enough to capture enough of the surrounding landscape to show the context of the vegetation patterns (Figure 1). Rainfall is relatively low across the area (450–500 mm pa), due to the rain-shadow of the Otway Ranges (Jones, 1999). Most of the land surface in the study area is composed of relatively recent lava flows, generally between 4.5 and 2.2 million years old (Stewart 1977, Rosengren 1999, Hare *et al.* 2005, Gray and McDougall 2009). These form flat or undulating plains. Drainage patterns are irregular and poorly formed, and are still influenced by the paths of the lava flows. Soils are fertile (by Australian standards), shallow and ‘heavy’ (small particles), with many basalt rocks at or near the surface. Water- or wind-deposited material (parna, sand) from non-volcanic sources may also occur on the surface (Geraghty 1971, Jones 1999).

Several rivers flow across the area. Some, notably the Werribee, are in deep rocky gorges, cut relatively recently during a period of stream renewal when sea levels were lower than today (Rosengren 1986). The lower Werribee is flanked by the so-called Werribee ‘delta’, an area that is covered by rich soils deposited by the Werribee and its now-abandoned system of distributaries when the river was not so entrenched (Rosengren 1987). The ‘delta’ is now used largely for market gardening.

The study area includes the You Yangs in the south west, a range of hills composed of Devonian granite (364 m at Flinders Peak). These hills retain their complex patterns of woody vegetation, and are not dealt with in detail here. The study area also includes soils deposited on the beds of lakes and swamps, and an array of places with differing local geologies not dealt with in this overview (such as sedimentary exposures from beneath the basalt plain).

## Methods

Four distinct types of data were collected separately and combined to produce a vegetation map. Firstly, the study area was examined in the field. Relict trees were identified and mapped. The precise positions of the trees (within ~20 m) were recorded either using a GPS, or by locating the trees on geo-referenced digital aerial photographs. Trees were mostly identified from roadsides using binoculars, or occasionally from gaining access to paddocks. The spatial coverage of this dataset is incomplete and spatially biased (given the idiosyncratic pattern of tree clearance since 1835 and our inability to adequately view all areas). Relict trees are generally distinguishable from planted trees, through some combination of the following: 1) they are of local species rarely planted, 2) they often occur in irregularly-shaped stands across multiple paddocks or as isolated trees away from paddock margins, 3) they often occur in mixed age stands, 4) they are often large or display ‘old-growth’ forms. Fortunately, the species relevant locally are fairly easy to distinguish from a distance. Trees of doubtful identity were either ignored, or used only to make a distinction between *Eucalyptus* and *Allocasuarina*, or to discount absolute treelessness. Where dense stands of trees occurred, a patch was delineated and the main species noted. In a few cases where stands of trees, apparently of a single species, could only be seen in the distance, the air photo was used to guess the coverage of parts of the stand that could not be clearly seen. Several species of tree are very rare locally, and without any evidence that they were once more common, formed no part of the current analysis: Werribee Blue Box *Eucalyptus baueriana* subsp. *thalassina* occurs on riparian terraces and a few depressions among Grey Box; White Box *Eucalyptus albens* occurs very rarely with Grey Box; several *Acacia* species occur on escarpments, and White Cypress-pine *Callitris glaucophylla* occurs on a few escarpments.

Secondly, we consulted early reports and diary entries to gather descriptive information and illustrations. These sources are cited in the text.

Thirdly, historic plans with information relating to the original native vegetation were retrieved from the microfiche collection at the Public Records Office of Victoria (PROV; this collection is replicated in the State Library). As the plans are not fully catalogued, several sections of the Historic Plans Collection were examined in full (Coastal Surveys 1–171, District Plans 1–87, Features Plans 1–683, Grazing Blocks 1–18, Early Melbourne 1A–128A, Miscellaneous Roll Plans 180–Y104, Pastoral Run Plans 1–1370, Roll Plans 1–136l Sale Plans A–702, Special Surveys 1–6B, Sydney (prer-1851) A1–Y10). This revealed a number of useful plans, including several not used by McDougall (1987) in his reconstruction.

Four types of information were extracted from the plans:

1) Forest boundaries. Some plans include line-work showing the boundaries of forests and treeless plains, clearly labelled. These could be directly traced.

2) Annotations on vegetation. Most appear as text, spatially unbounded on the map. These comments help to categorise an area, but not to bound it.

3) Stylised depictions of trees (e.g. stippling). These presumably represent scattered or diffuse patches of trees where no distinct boundary was obvious to the surveyor. These could be 'traced', but only doubtfully. In these cases, aerial photographs and digital elevation data (CSIRO 2010) were used to find on-ground features (rocky rises, wetlands, etc) to guide likely boundaries.

4) Lot corner markers. In the early phase of settlement, lands newly marked for sale or selection were marked in the field by marked trees, cairns, mounds or trenches. Where trees were used, these were identified and their precise position in relation to the lot corner was noted, in terms of a bearing and a distance. Some examples are ambiguous as to whether the bearing is from tree-to-corner or corner-to-tree; no standard method seemed to exist. Fortunately the distances are small (mostly within one chain, i.e. 20.12 m), and we assumed that trees were located at the lot corner. In most cases the cadastral boundaries have remained unchanged since the original survey, so re-locating the corners was a trivial task. Importantly, corner marks also revealed areas that were treeless or sparsely treed. Earth marks or cairns were only used when no substantial tree was nearby, certainly not within a chain (this is evidenced by the comment 'no tree near' which is used frequently when an earth mark or cairn is used).

Fourth, digital ortho-aerial photographs (2007, 2009) were examined carefully to identify clues in the colour of the soil and the presence of rocks. Wetlands and creeks were mostly identified in this way (visible as greyish patches). We also examined historic aerial photographs, but found they did not significantly add to the information gained from other sources.

The information was combined using a Geographic Information System (GIS, Arcview 3.2, ESRI). Most plans were geo-rectified (digitally stretched into alignment with a base map, Arcview 3.2 & ImageWarp 2.0) so their features could be traced directly. Information from other plans was recorded 'by eye', in cases where geo-rectification was not practical (e.g. due to too few reference points).

The following principles were used to guide decisions where the evidence was equivocal:

The default type was treeless grassland; assigned wherever there was no evidence for trees or a wetland. This reflects the fact that this map is designed to assist revegetation, and considers inappropriate tree-planting in former grassland to be less desirable than a missed opportunity to plant trees.

Wetlands within a treed area were considered to be Treed Wetlands. Other wetlands were considered treeless, unless there was positive evidence of trees.

Existing stands of relict trees took precedence over the information on plans. The boundaries shown on the plans were often close to the existing tree boundary, in which cases the boundaries were shifted slightly by hand.

Isolated relict trees that did not form part of a treed area recorded on the historic plans were enclosed within a circle of 50 m radius, and assigned to a type based on the species. The surrounding area remained treeless.

The Victorian Government currently describes vegetation according to Ecological Vegetation Classes (EVCs, Woodgate *et al.* 1994). An EVC encompasses areas of vegetation (one or more floristic communities) that show consistent form, context in the landscape, and ecological function. The historic record does not, however, always align neatly with this system, and EVCs are here only used as secondary descriptors of the vegetation. The main typology employed here is simple (see below), and was formed by the constraints of the available evidence. The words 'forest' and 'woodland' are used loosely throughout this paper, often as they appear on the primary sources, without strict reference to cover or height thresholds. There is no way of knowing with any precision what the tree density was in most places.

Riparian and escarpment vegetation is not addressed in any detail here. These vegetation types are patterned too finely to be resolved at the scale of this investigation, and remain sufficiently intact for contemporary surveys to discern their character. These vegetation types are shown on the map (Figure 2) in the same style as "treed wetlands". Similarly, the 'delta' is not treated here, as it does not fall within the grassland reserve areas, and is poorly represented in historical sources. As well the 'delta' has been severely altered by a long history of development (market gardening, urbanisation and the Western Treatment Plant).

## Results

### *The vegetation*

The results of our research are synthesised to create a map showing a reconstruction of the vegetation patterns on the Werribee Plains before colonisation (Figure 2). Figure 3 shows the evidence base used to construct the map. Several distinct types of vegetation were distinguishable.

Forest dominated by Grey Box *Eucalyptus microcarpa*. Early records make it clear that forest areas were quite distinct from grasslands, and most early surveyors were prepared to draw confident boundaries on the forest patches (Anon 1838, Darke 1839a, b, c, 1840, 1841, before 1858, Hoddle 1850). Hovell (1824, *in* Moloney *et al.* 2006) described

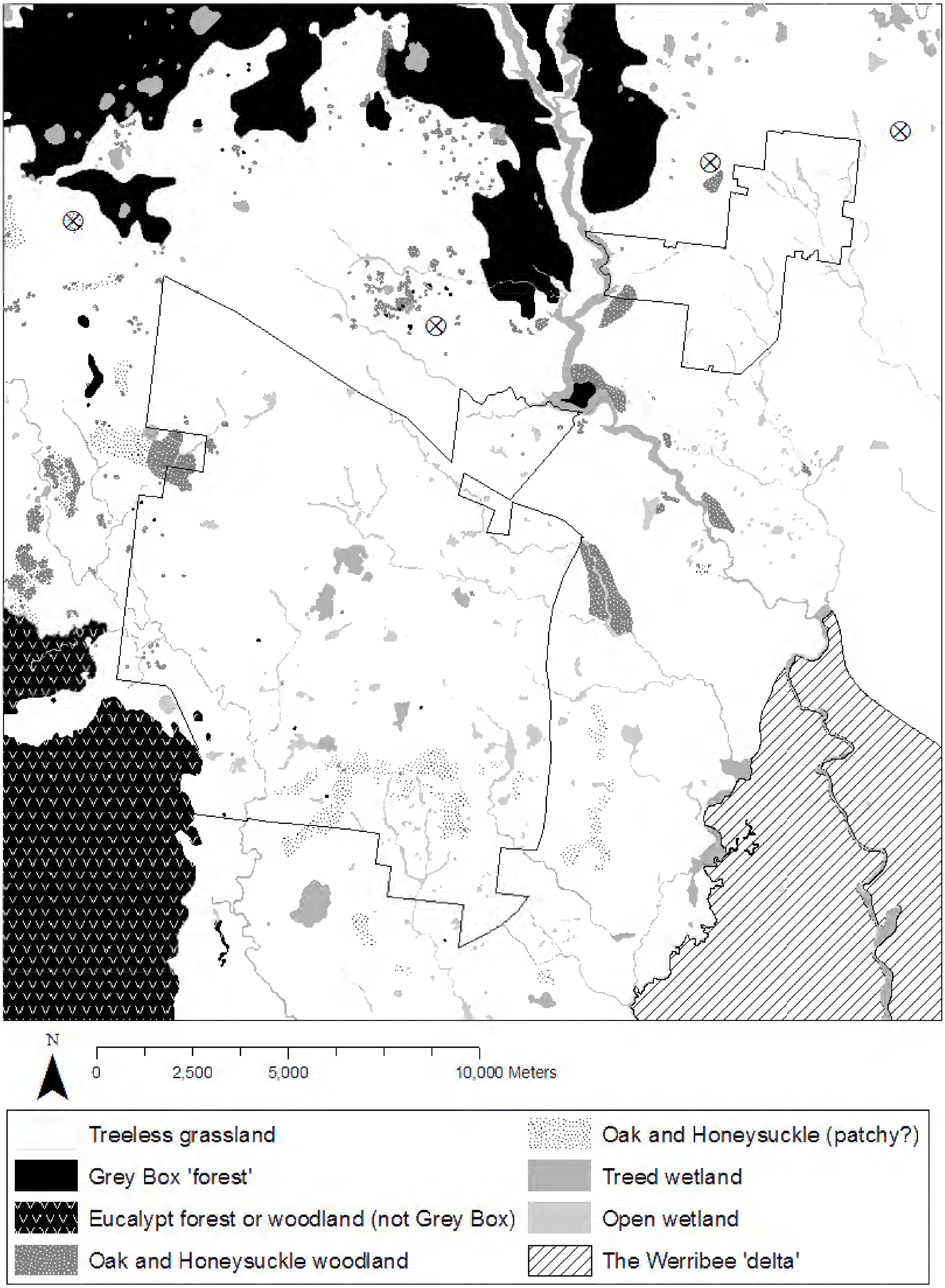

**Fig. 2.** Reconstruction of pre-colonial vegetation patterns on the Werribee Plains. The crossed circles represent prominent volcanic eruption points.

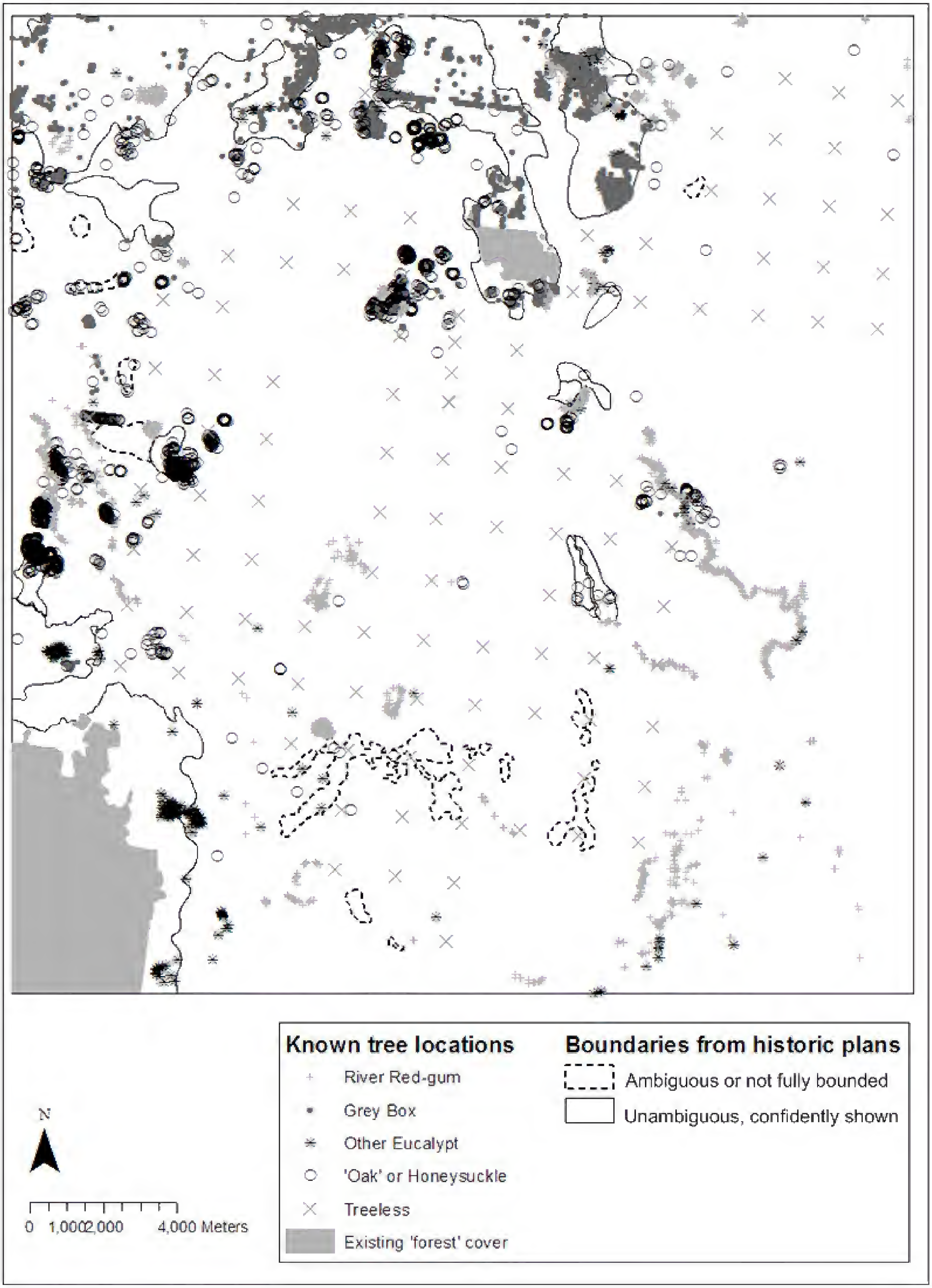
Known tree locations
River Red-gum
Grey Box
Other Eucalypt
'Oak' or Honeysuckle
Treeless
Existing 'forest' cover
Boundaries from historic plans
Ambiguous or not fully bounded
Unambiguous, confidently shown
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**Fig. 3.** Summary of the evidence used to construct the map.

areas near Melton with "patches of forests which appear to separate one plain from another", and noted "it is all plains and small forests". Remnants of these 'small forests' remain in relatively intact form at Eynesbury and Pinkerton, allowing their character to be seen first hand (e.g. Geraghty 1971, Ashby *et al.* 2007). Although they occur on basalt, the forests show obvious affinities with northern Victoria, highlighting the fact that the Werribee Plains are an outlier of relative aridity south of the Dividing Range (Jones 1999). The forests are strongly dominated by Grey Box *Eucalyptus microcarpa* (described in some early sources as 'Peppermint'), with occasional specimens of other trees (e.g. Yellow Box *Eucalyptus melliodora*, Buloke *Allocasuarina luehmannii*). Shrubs are moderately common, above a sparse grassy layer composed largely of Spear-grasses and Wallaby-grasses (*Austrostipa* spp. and *Rytidosperma* spp.). Several early reports commented on the sparse ground layer. Wedge (1835) noted "there is not much grass in the forest". Hoddle (1850) was the most emphatic, describing the Eynesbury forest as "…wholly destitute of grass." These forests are described as 'Plains Woodland' under the current EVC vegetation typology (Oates and Taranto 2001, Ashby *et al.* 2007). This vegetation type was virtually absent from the grassland reserves, and should not be the target of restoration within their boundaries. Grey Box Forest is shown in Figure 4.

Eucalypt forest or woodland not dominated by Grey Box. Forests or Woodlands of Red Box *Eucalyptus polyanthemos* and other species cover the eastern slopes of the You Yangs, the granite hills in the west of the study area. These are fairly intact, their character remains evident, and they will not be described further here. Interestingly, however, Red Box trees extended off the granite, and onto the basalt plain in some places (along with Yellow Box *Eucalyptus melliodora* and Yellow Gum *Eucalyptus leucoxylon* subsp. *connata*). We could find no reference to these treed areas in written historic accounts, and historic plans show only minor incursions of forests or woodlands onto the basalt plain around the You Yangs (Darke 1841, Colbert 1855). Scattered but numerous relict trees, however, show beyond doubt that Red Box extended eastward from the You Yangs well onto the basalt plains, up to ~7 km away from the apparent edge of the granite. Darke (1841) drew a few stylised trees on the plains in these areas on his survey map, perhaps suggesting a diffuse and sparse coverage. The character of these woodlands can only be gauged by a few existing sites on roadsides, where the understorey is very similar to that of the treeless grasslands described below. It is difficult to judge how this vegetation relates to the EVC typology, but is probably referrable to Plains Grassy Woodland (Oates and Taranto 2001). Its occurrence in the grasslands reserves was patchy and minor. Given the difficulty in defining its exact extant, and the desire not to 'over plant' trees in the grasslands reserves, the restoration of this woodland type should probably be restricted to the areas immediately around the existing relict trees. This vegetation type is not pictured.

Treeless grassland. Flinders (1802 *in* Moloney *et al.* 2006) was the first to describe the Werribee grasslands, recording that the plains were "covered with small-blade grass but almost destitute of wood, and the soil was clayey and shallow." Batman (1835) described the plains in detail "…with scarcely any timber, and covered with Kangaroo grass eight and ten inches high. This I think is the average. Most beautiful sheep pasturage I ever saw in my life," and "beautiful plains of the best description of grass". The character and composition of the grassland vegetation is well known (Sutton 1916–17, Patton 1935, Willis 1964, Stuwe and Parsons 1977, Carr 1999). It was dominated by tussock grasses (Poaceae), particularly Kangaroo Grass *Themeda triandra*, Spear-grasses *Austrostipa* spp., and Wallaby-grasses *Rytidosperma* spp. (The current lack of Kangaroo grass in most 'native' paddocks in the study area is likely a management artefact, as most roadsides across the area support this species). Between the tussocks grew a diversity of other plants, notably broad-leaved native herbs, including many daisies (Asteraceae), geophytes (Lileacae, Orchidaceae), and some deep-rooted perennial sub-shrubs (such as *Pimelea* spp.). The areas mapped here as Treeless Grassland also encompass numerous small stony knolls, which are the result of uneven lava surfaces. These areas are often too small to show at the scale of mapping. Today, these differ from the grassland plains in supporting a few shrubs, such as *Acacia paradoxa* and *Bursaria spinosa*. A few early sources described shrubs or bushes on the plains (e.g. Fleming 1803), but it is not clear whether these were only on stony areas. The shrubs may have been large shrubs such as Sweet Bursaria *Bursaria spinosa* or *Acacia* spp., still common on rocky rises; smaller species such as Tree Violet *Melycitus dentatus* or possibly very small shrubs still present in the treeless grassland areas such as *Maireana* spp. and *Pimelea* spp. The grassland vegetation is referrable to the EVC Plains Grassland. It is listed under the EPBC Act as 'Natural Temperate Grassland of the Victorian Volcanic Plain', and under the *Flora and Fauna Guarantee (FFG) Act* 1988 as 'Western (Basalt) Plains Grassland Community'. The stony knolls are referrable to the EVC Stony Knoll Shrubland. Restoration of grassland vegetation with trees is inappropriate, although many small woody shrubs may be considered. Treeless grassland vegetation is pictured in Figure 5, and small shrubs in Figure 6.

Non-eucalypt woodlands of 'Oak and Honeysuckle'. Many areas now devoid of trees once supported open woodlands of She-oaks (both Drooping She-oak *Allocasuarina verticillata* and Buloke *Allocasuarina luehmannii*) and 'Honeysuckle' (*Banksia marginata*). For example, Hoddle (183?) described the plains of Tarneit as "broken by ridges of trap, moderately timbered with Honeysuckle and She oak." There is evidence that these stands of trees often occurred in discrete patches and clumps. Batman (1835) "passed a small forest, about two miles in length, of she-oak; about eight or ten to the acre[1], and from twelve inches downward in size" Colbert (1855) described "scattered *clumps* of timber" near Balliang Creek. Hoddle (1850) described the Plains around Wyndham Vale as "open plains lightly timbered with she oak". Campbell (1906) describes Oaks too, "*isolated clumps* of which brave the wind and stand out on the plain". Oaks and Honeysuckles are also frequently used as lot corner markers (Darke 1839a, b, 1840, 1841, before 1858, undated). This vegetation has now become extremely rare locally. Oak and Honeysuckle woodland evidently once occurred on flat to undulating heavy-soil plains (most evidence for Buloke *Allocasuarina luehmannii*, some evidence for Honeysuckle), and also on stony rises (most evidence for Drooping She-oak *Allocasuarina verticillata*, some evidence for Honeysuckle); suggesting that two rather different ecological entities are included here, one on stony rises, one on plains (discussed further below). The scant evidence suggests that the lower storey of this vegetation closely resembled the open grassland and stony knoll vegetation respectively; indeed many areas which apparently once supported these woodlands are now recognised and mapped as the EVCs Plains Grassland or Stony Knoll Shrubland (Growth Areas Authority 2010a–d). Numerous historic sources (mostly parish plans not cited here) suggest that these vegetation types have disappeared from much of lowland Victoria, and their decline is worthy of further study. These non-eucalypt woodlands are probably under-represented in Figure 2, given their frequent mention in comments on plans, without any further evidence from other sources. These areas of former non-eucalypt woodland should be a priority for restoration; given their depletion and the fact that their former character probably provided resources for animals (cones, nectar) that are now largely absent from the local landscape. Many small clumps of woodland may have disappeared without trace. It is likely that inspection of all areas on ground may reveal the presence of unnoticed stumps, leaving open the hope that some further areas of non-Eucalypt woodland can be identified. Figure 7 shows Bulokes (*Allocasurina luehmannia*) growing on the plains and Figure 8 shows a Honeysuckle (*Banksia marginata*) growing on a stoney rise.

Open wetlands. Flinders (1802; *in* Moloney *et al.* 2006) described the Werribee Plains from the You Yangs as a "low plain where the water appeared frequently to lodge". Similarly, Grimes (1803) noted that "there are marks of water laying much on these plains." Howitt (1855) described that after rain the "plain underfoot was soon one universal pool". Heavy rains in 2010–11 again illustrated that water pools readily on the plains. Ephemeral wetlands (vernal pools) large and small are still so numerous it is difficult to map the smaller ones. Depending on their hydrological regime, treeless wetlands support a range of plants, with some rarely-inundated sites barely distinguishable from the surrounding grasslands; others supporting a sward of Common Tussock-grass *Poa labillardierei*; some supporting Tangled Lignum *Muehlenbeckia florulenta* or Barren Cane-grass *Eragrostis infecunda*. The wetlands require a number of EVCs to adequately describe their diversity. The most prominent include Lignum Wetland, Ephemeral Drainage Line Grassy Wetland, Cane Grass Wetland, and Plains Grassy Wetland (DSE 2009b). This vegetation type is not pictured.

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[1] i.e. roughly 20 m between trees.

Treed wetlands. The more substantial, deeply and/or frequently inundated wetlands support River Red Gum *Eucalyptus camaldulensis*, frequently above large expanses of Barren Cane-grass *Eragrostis infecunda* and clumps of Tangled Lignum *Muehlenbeckia florulenta* and a range of herbs. These treed wetlands are curiously absent from some plans that show forest boundaries (e.g. Darke 1840, 1841). Howitt (1855), trying to find shelter while passing between Geelong and Werribee in 1854 "descried a few trees some couple of miles off" but "to our consternation we found, on arriving at them, that these trees grew in a great swamp." Campbell (1905) states that "…on the plain in curious gnarled clumps stand *E. rostrata* [now *E. camaldulensis*] with fine white barrels." Even the most substantial and long-inundated treed wetlands on the Werribee Plains are to some degree ephemeral, and presumably always have been (Nixon (1859) labels one "Dry some years past"). Treed wetlands are generally assignable to the EVCs Red Gum Swamp or Lignum Wetland (DSE 2009b). Figure 9 shows a treed wetland in its context on the Werribee Plains.

## Discussion

### *The origins of the patterns*

Why did trees occur in some places, but not others? The reasons for treelessness in lowland grasslands have long been discussed, in southern Australia (Sutton 1916–1917, Patton 1935, Willis 1964, Geraghty 1971, Morcom and Westbrooke 1998, Jones 1999, Gammage 2011) and worldwide (e.g. Coupland 1979). It is generally agreed that moisture stress excludes trees. This is a function not of rainfall alone, but also the soil. Soils with fine particles, such as those clays formed on recent basaltic flows, make it physiologically difficult for plants to access water (at least during some critical times of the year) and are antagonistic to woody plant growth in low-rainfall areas. Soil cracking and shrinking in summer presumably exacerbates drought stress (Willis 1964). The occasional presence of trees in lowland grasslands is generally attributed to local factors (rockiness, small depressions, etc) subtly alleviating moisture stress.

There are relatively few experimental studies that directly link soil properties with treelessness, however one relevant study examined soil properties along a transect running from naturally treeless grassland to Grey Box forest (Rockbank to Eynesbury; within the current study area, Geraghty 1971). A link between soils and treelessness was reported; with Grey Box forest restricted to soils with quartz sand or pebbles, which are able to ameliorate the effects of the clays. Geraghty (1971) noted that this quartz was not basalt-derived, but was probably brought in by wind or (more likely) floodwaters associated with landscape reconfiguration brought about by the formation of the tectonically-controlled depression known as the Port Phillip Sunkland. This depression encompasses the lowlands of Melbourne, and is bounded in the study area by the Rowsley fault, beyond which the Brisbane Ranges and the hills of Ballan and Bacchus Marsh rise.

It is interesting to note the current distribution of forests and grasslands in relation to the existing major water courses. The forests follow the Werribee River downstream in bands on either side (Eynesbury and Pinkerton Forests; upper-centre in Figure 2). The ancient flooding which brought quartz material onto the basalt plain presumably followed roughly the same low-lying course as the current Werribee River. It is clear, however, that the Grey Box forest was once separated from the river gorge by bands of treeless grassland. This pattern is repeated on Toolern and Parwan Creeks. These bands of grassland were 50–350 m wide, and several kilometres long (Figure 2). The historic record leaves no doubt that this pattern was evident before colonisation and is displayed on all the relevant maps (Darke 1839a, b, c, d, 1840, 1841, 1858, Hoddle 1850). Wedge (1835) describes a "belt of forest trees" before meeting the Werribee River near Exford. The treeless strips separating the "belts" of forest from the gorge warrant further investigation. They may be associated with the removal of the coarser quartz material near the gorge edges as the gorge was cut, and / or may be cultural artifacts associated with aboriginal land management.

Some authors suggest that frequent fire also contributes to the exclusion of trees from grassy landscapes, including fires lit by humans over a long period as a management tool (Morcom and Westbrooke 1998, Bredenkamp *et al.* 2002, Yugovic and Mitchell 2006, particularly Gammage 2011). The Werribee plains were clearly burnt regularly and extensively before colonisation: Fleming (1803) noted that the grass visible on the Werribee Plains from the top of a hill was "mostly newly burnt" in February. Hovell (1824 *in* Moloney *et al.* 2006) notes that "the grass does not appear to have grown more than two or three inches since it was burned last year". Batman (1835) described the grass on the Werribee Plains as "three feet high where it had not been burnt late in the autumn, which is the case in most parts." King (1837, *in* Moloney *et al.* 2006) notes that around Melton a "great part of herbage recently burned", and describes the Little River area as "a most arid waste; the grass had been burned off." Such fires would have inevitably affected the vegetation.

We believe that the effects of fire are less able to explain the distribution of Eucalypts than the interaction of rainfall with soil. The plains beyond the *Eucalyptus* tree-line were clearly occupied by woodlands of 'Oak' (*Allocasuarina* spp.), sometimes with Honeysuckle (*Banksia marginata*). Those non-eucalypt trees are generally 'less tolerant' of intense fire than *Eucalyptus* (Macaulay and Westbrooke 2003), and almost all conceivable fire regimes could not exclude the local *Eucalyptus* species while allowing *Allocasuarina* and *Banksia* to persist. Admittedly, frequent, low-intensity fire may be able to kill eucalypt seedlings but allow Bulokes to persist via suckering (Morcom and Westbrooke 1998); although this line of argument is less applicable to *Banksia* or *Allocasuarina verticillata*. The treeless strips noted above -between rocky gorges and forest- could not be maintained by fires without very precise and deliberate fire control. It is possible that these strips were carefully maintained for some purpose by aboriginal people; but any such purpose is now lost. The soil-related reasons discussed above for the absence of *Eucalyptus* on the plains seem far more convincing.

While we doubt a major role of burning in regulating Eucalypt distribution, it may have had a more important role in relation to *Allocasuarina* and *Banksia*. These species can, under the right conditions, form dense stands. Despite this, the historic record confirms that they were present as woodlands in clumps and patches. For example, Batman (1835) described a discrete patch of She-oak forest at a density of "about eight or ten to the acre". Fire may once have been an important factor in preventing their local proliferation; with these species persisting in places where fire was less regular and/or less intense. The pattern of Oak and Honeysuckle distribution may well have been influenced by aboriginal burning. Some authors (notably Gammage 2011) argue that aboriginal people deliberately created clumps and lines of trees to assist hunting. This is compatible with, but unproven by, the evidence for the Werribee Plains.

On the largely treeless plains, it would seem that Drooping She-oak (*Allocasuarina verticillata*) was particularly prominent on stony rises (Anonymous (1845) described "…ridges timbered lightly with she-oaks"), which may have provided some degree of fire-protection. In contrast, Buloke (*Allocasuarina luehmannii*) was probably more prominent on the non-rocky plains, where it could survive fires by suckering, thus forming the clumps mentioned above (Figure 7). Unfortunately, the evidence for this patterning is complicated by the fact that the term "oak" was used freely in the nineteenth century to describe both *Allocasuarina* species (Morcom and Westbrooke 1998). Current observations (locally and elsewhere in Victoria) do, nonetheless, hint at a separation of the two species between the rises (Drooping She-oak) and the low plains (Buloke). The position of *Banksia marginata* on the plains is less clear. Records are located on stony rises (Figure 8), volcanoes and on non-rocky plains, but this species is so depleted that it is difficult to make any judgement on its ecological preferences without further research. Emphasis is given here to the non-Eucalypt species' distribution on the plains beyond the *Eucalyptus* stands; but these species were probably once also present within the 'Grey Box Forest', where fire intensity was presumably relatively low. Both *Allocasuarina* species still occur there.

After 1835, the factors shaping the vegetation changed abruptly. While the fundamental ecological processes related to climate, soils and competition continued; new and overwhelmingly powerful forces changed the vegetation markedly, to produce the largely-cleared landscape we see today. The most obvious of these changes to affect tree distribution was the cutting of timber. The removal of discrete 'chunks' of Grey Box Forest, often following the edges of paddocks or properties, is an obvious result. Less obvious is the cutting of *Allocasuarina* species from the plains beyond the forests. There is some evidence that She-oak woodlands were preferentially removed for firewood (Howitt 1855, Hately 2010). Banksia woodlands presumably suffered a similar fate, but their demise may have been hastened by their palatability to sheep.

## Conclusions

We hope that the data presented here will help illuminate Melbourne's relationship with the natural environment. There has been renewed interest recently in how natural geography has shaped Melbourne (e.g. Moloney *et al.* 2006, Boyce 2010), and it is clear that the presence of the grasslands was a major reason for Melbourne's existence, and a major influence on its development. This study should add much-needed detail to that narrative. The locations of land claims, homesteads, tracks and roadways may all be better understood with reference to the very fine-scale vegetation patterns revealed here.

We also hope that our findings will help us manage and plan for future changes to the landscape. One of the main motivations for this study was to inform ecological restoration. Historical vegetation maps are only one ingredient in a program of ecological restoration. Restoration also includes philosophical, technical and social considerations.

The technical challenges of restoration are significant. The 'template' presented here only tells the story of tree distributions. Restoration will require a more subtle understanding of small-scale spatial and temporal patterning in non-woody plants. It will also require technological knowledge about *how* to restore these systems efficiently.

Using historic maps as guides for restoration is also fraught by non-technical difficulties of interpretation. The most difficult problem is that it may be impossible to distinguish stable patterns from transient patterns; and culturally created boundaries from physically determined boundaries. There is a risk of considering the patterns of the mid-nineteenth century to be somehow sacrosanct; when they may really have been in flux, and may not represent the vegetation configuration which best conforms to the underlying physical and ecological drivers. The most sensible response to this seems to involve being explicit about our interest in the *historic* values we seek to preserve and re-create; admitting that in the absence of a better template, the 'pre-1750' is a practical alternative that we know was the home of the vanishing 'values' we seek to protect; and lastly, by assessing the long-term success or failure of restoration attempts which may eventually reveal subtle physical constraints we do not yet understand.

## Acknowledgements

We thank Frances Overmars (Pinkerton Landcare and Environment Group), Dr John Morgan (Latrobe University), Matt White (DSE) and Colleen Miller (Western Melbourne Catchment Network) for useful discussions and for pointing us to several useful references. We thank Dr David Duncan (DSE) for comments on an early draft. We also thank Bryan Campbell for permission to use the diary of A.G. Campbell. Photographs were kindly provided by Maarten Hulzebosch (Figure 6) and Damien Cook (Australian Ecosystems Pty Ltd, Figure 7).

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Note: The early plans are unpublished documents, with incomplete and inconsistent bibliographic information: Some are anonymous, undated and/or untitled; others are copies of earlier maps. We cite them according to the surveyor (not the lithographer, etc), or as 'Anon.' if no surveyor's name was given. We date them from the date of the survey (not subsequent copying). If no survey date is given, the earliest date of copying is used, preceded by the word 'before'; others are entirely undated. The following abbreviations are used for the microfiche collections from the Public Records Office of Victoria (PROV): SP Sale Plan, FP Features Plan, RP Roll Plan, S Sydney pre-1851.

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Manuscript accepted 16 April 2012

## Appendix 1 Photographs

The following photographs have been selected to show what the vegetation of the Werribee Plains may have looked like in its pre-colonial state. Photographs have been selected which typify most of the vegetation types mentioned in the text. Places with mature vegetation structure, few weeds and no human infrastructure have been preferred. All are taken within the study area, expect Figure 7, which was taken further west (near Dundonnell), because no vegetation representative of Honeysuckle or Oak on stony rises could be found closer. All of these photographs show places which are now rare relicts; most of the Werribee Plains is today agricultural or urban in character.

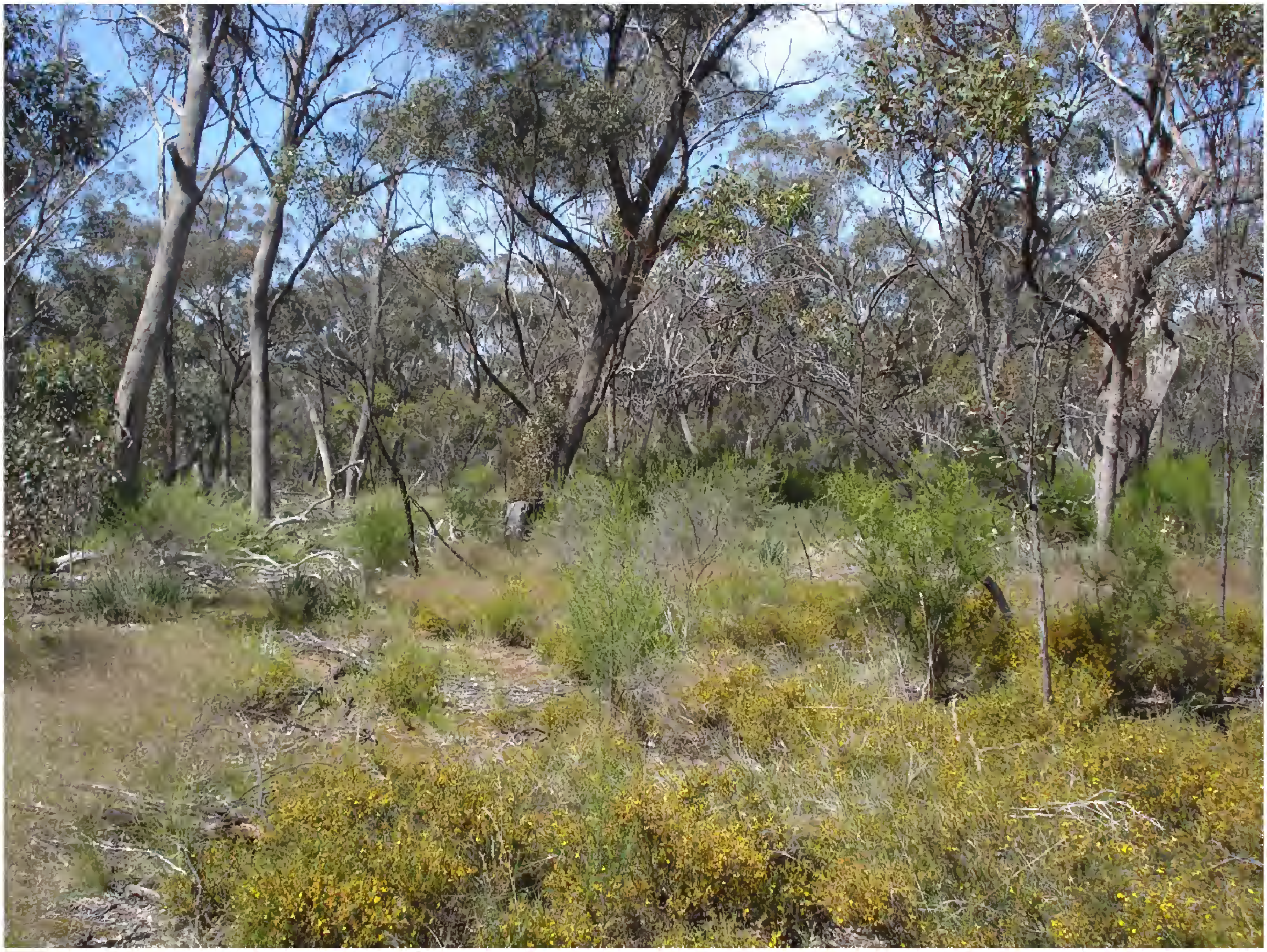

**Fig. 4.** Forest dominated by Grey Box (*Eucalyptus microcarpa*), in Eynesbury Forest, within the study area. Note that the ground layer is sparsely grassed. Flowering plants of *Eutaxia microphylla* are visible in the foreground.

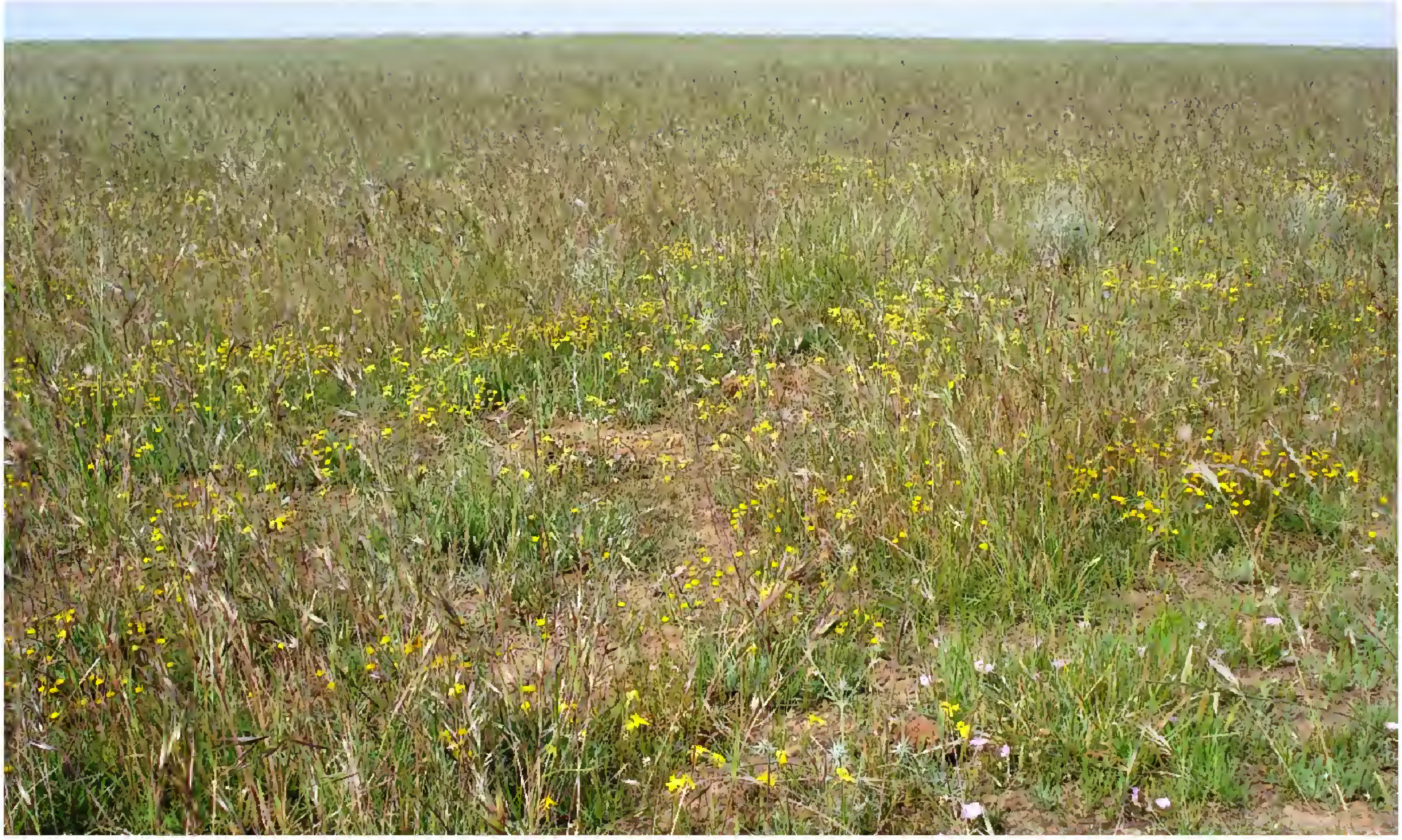

**Fig. 5.** Treeless Grassland, near Manor within the study area, photographed in Spring when the herbs are flowering and the summer-growing dominant grass *Themeda triandra* is in early growth. The flowers which are most prominent include *Leptorhynchos squamatus* (yellow) *Goodenia pinnatifida* (yellow), and *Convolvulus angustissimus* (pink).

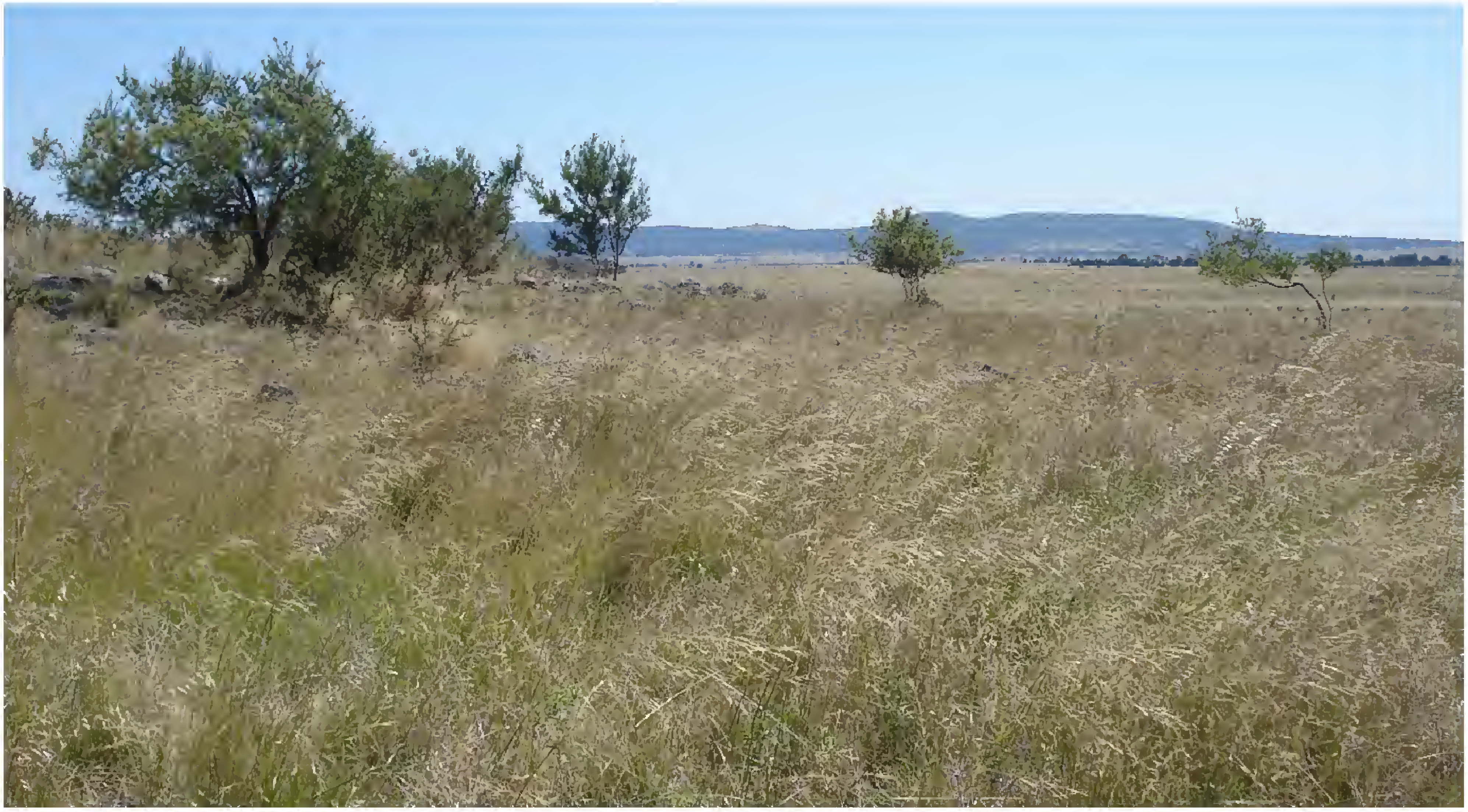

**Fig. 6.** Shrubs on a small stony rise within open grassland, taken at Manor, within the study area. The shrubs are *Bursaria spinosa* and *Acacia paradoxa*. The dominant grass in the foreground is *Austrostipa bigeniculata*.

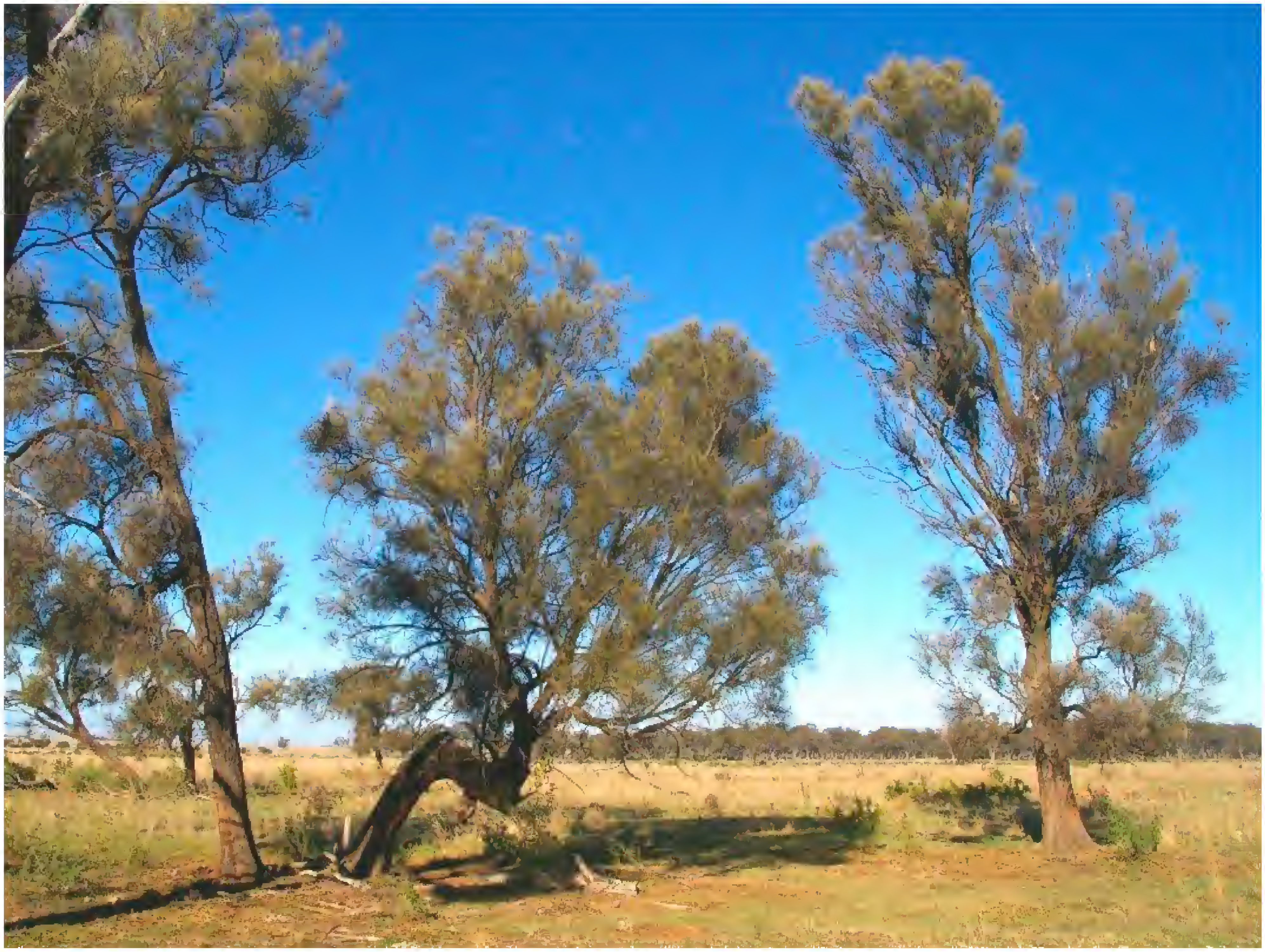

**Fig. 7.** Non-eucalypt woodland of 'Oak'. Here, *Allocasuarina luehmannii* grows on the plains near Exford, within the study area. Note that the discrete boundary of the *Eucalyptus microcarpa* forest is visible in the distant background. Photographed by Maarten Hulzebosch.

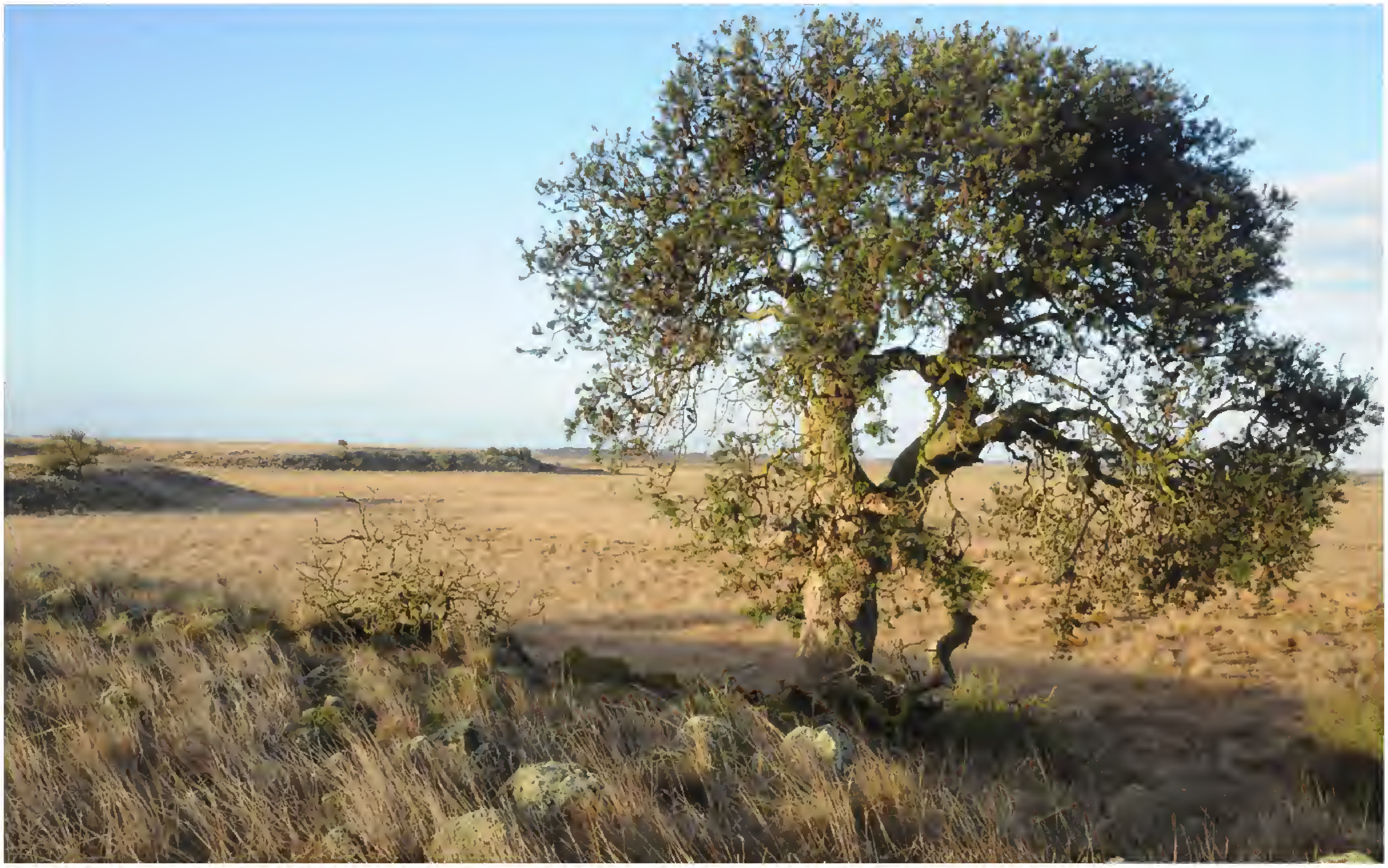

**Fig. 8.** Non-eucalypt woodland of 'Honeysuckle'. Here, a single individual *Banksia marginata* remains, growing on a stony rise. No woodlands on stony rises could be photographed within the study area. This photograph was taken further west, near Dundonnell. Photographed by Damien Cook.

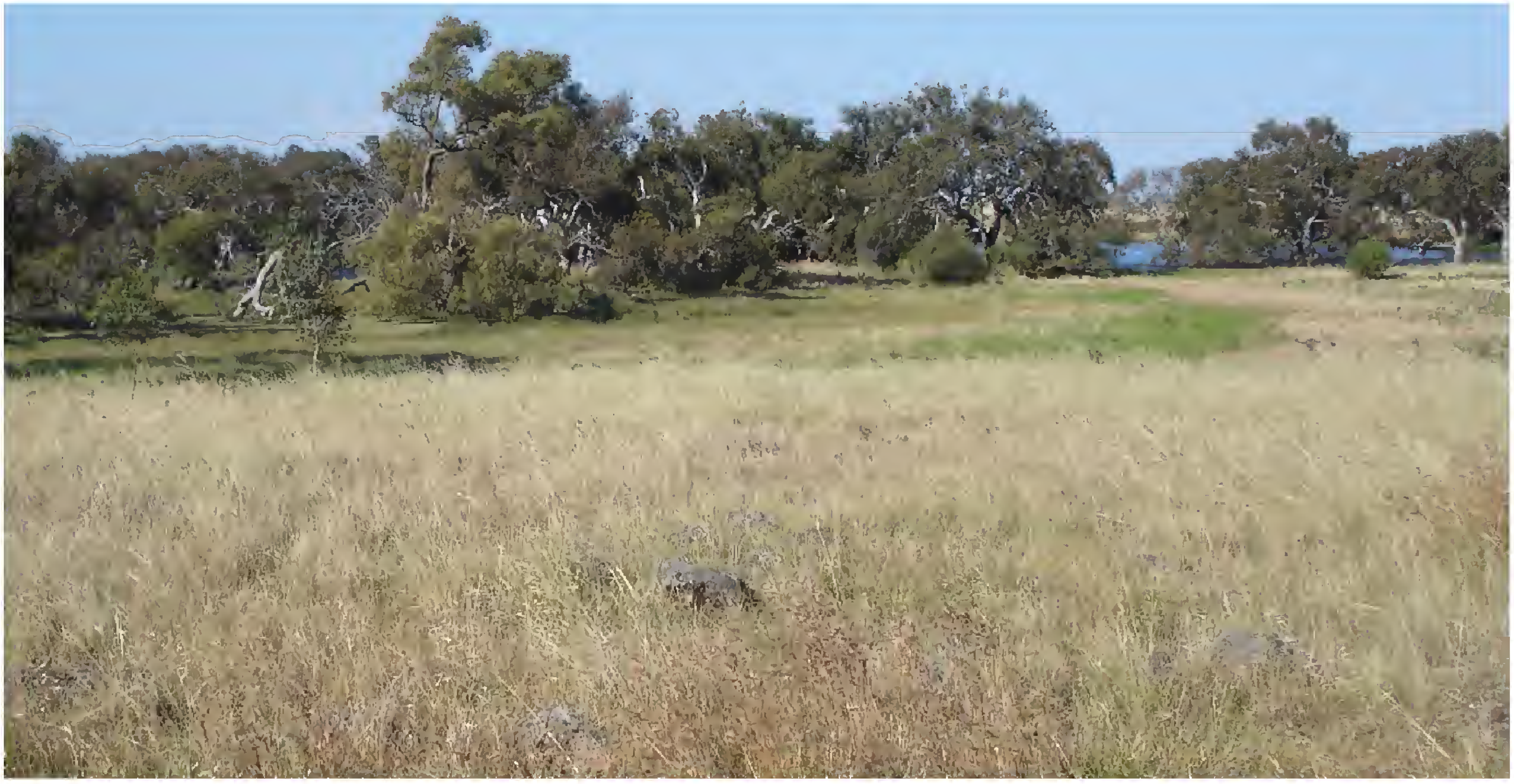

**Fig. 9.** Treed Wetland. Grassland dominated by *Themeda triandra* (foreground) grows on the high ground at front. In the lower ground at the rear, mature trees of *Eucalyptus camaldulensis* grow in a wetland, with a lower layer of *Eleocharis acuta* and patches of open water. This photograph was taken at Richmond's Swamp, within the study area.

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Date of Publication:
30/07/2012

Cunninghamia
A journal of plant ecology for eastern Australia

The Royal
Botanic Gardens
& Domain Trust

ISSN 0727-9620 (print) • ISSN 2200-405X (Online)

# The Grose Vale flora and the value of documenting botanically interesting sites

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***Abstract*:** Particular botanical sites have always been attractive to botanists, and the recording of such sites even in an *ad hoc* way, adds to our long-term documentation of ecological change. Here we look at records from an unusual dry rainforest site in western Sydney, first recognised in 1910, and re-recorded on several occasions more recently. Though the site has little formal conservation protection, the records indicate that many of the original species still survive at the site, while the periodic recording draws attention to the scientific value of the site, particularly at a local level, and has increased its value as an ecological reference site.

Much of the vegetation of the Cumberland Plain has been subject to major clearing and disturbance over the past 200 years, and almost all vegetation is recovering in some way. Repeated visits are valuable for getting a complete picture of the flora; repeated visits by the same botanist over the shorter term (e.g. within a few years) may also be valuable, especially as the revisiting botanist may be more likely to notice changes. By documenting sites now, and continuing this over future years; we can enhance the value of many existing sites.

Key words: long-term monitoring, conservation management, Western Sydney Dry Rainforest

***Cunninghamia* (2012) 12(3): 229–238**
doi: 10.7751/cunninghamia.2012.12.018

## Introduction

Particular sites are always attractive to botanists. Such sites include those with locally different or relict floras, sites that stand out in the landscape for their particular geomorphology, geology etc, or sites where plants are part of the historical and cultural connections. In Australia such sites frequently include isolated mountain tops, hidden or sheltered valleys or gorges, and sites associated with botanical history such as Kurnell (visited by Banks and Solander in 1770). Sites along the routes of individual explorer-botanists, and often described or illustrated in their journals (e.g. Ludwig Leichhardt, Edmund Kennedy), are also likely to be revisited. Localised sites of particular interest may include hilltops, swamps, unusual geological outcrops, cave areas, cliffs and cultural sites (e.g. old cemeteries, mines, industrial sites). Serial visits to such sites often result in descriptive documentation or specimen collecting. For example the Mt Wilson – Mount Tomah basalt caps in the Blue Mountains west of Sydney, have provided plant collections (including those of Allan Cunningham, Jesse Gregson and Keith Ingram) and a series of scientific papers (Brough et al. 1924; Petrie 1925; McLuckie & Petrie 1926), while the dramatic Bulli escarpment inspired descriptions by Allan Cunningham (in Lee 1925) and Consett Davis (Davis 1936, 1941a,b). Other Sydney area examples are provided in Table 1. Because

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of their scenic, scientific, cultural or tourist interest, and/or intrinsic attributes (often steep topography or relative inaccessibility), these sites often survive local development pressures relatively intact or at least partially protected. Given the rate of landscape change in Australia over the last 200 years, and the paucity of long term studies, sites with some historic botanical documentation may play a key role in future long term studies. Depending on the individual site and its vegetation history, such sites may reveal details of how vegetation has changed over time (e.g. responses to disturbance, plant lifespans, vegetation resilience, rates of weed invasion etc), and how it is likely to respond to future change.

Western Sydney has been subject to grazing and agriculture for two centuries, and increasing areas of urban development for the last century, leaving native vegetation as remnants with increasing weed and management issues. A number of sites do have some historical botanical documentation, including Bents Basin where plant collections were made by the botanist-explorer George Caley in 1804, Joseph Maiden in the early 20th century, and more recently described as part of a rare species study (Benson et al. 1990). Unfortunately, at most sites, botanical material from the pre-1950 period is restricted to sporadic herbarium collections (Table 1).

Two sites are exceptions, the *Native Vineyard* at Cobbitty, and the *Limestone flora* site at Grose Vale. These sites were recognised over a century ago for their unusual botanical significance, and good contemporary descriptions of their vegetation were compiled. Both sites are clearly different from the surrounding country and were evidently different in the pre-European landscape. The *Native Vineyard* at Cobbitty was described by clergyman-botanist William Woolls in 1867 (Woolls 1867). Its dry rainforest/vineforest vegetation was clearly different from the surrounding Cumberland Plain Woodland, and Woolls listed many species that were unusual for the area (unfortunately no specimens collected by him appear to have survived). Woolls' interesting account drew several botanical collectors to the area in the 20th century including LAS Johnson and AE (Tony) Rodd in 1968; Robert Coveny and Doug Benson in 1976; Marie Kennedy in 1992; and Anders Bofeldt in 1996. A species list from 1976 was included in Benson (1992) and indicated that weed invasion by African Olive (*Olea europaea* subsp. *cuspidata*) was having a severe impact on the native vine and shrub species; it is understood that this unfortunate situation continues (P Cuneo pers. comm. 2011).

### *An interesting area of vegetation at Grose Vale*

In 1910 an interesting area of vegetation on limestone near Kurrajong drew the attention of W Mervyn Carne, at that time assistant botanist and assistant science master at Hawkesbury Agricultural College at Richmond (now part of the University of Western Sydney). Carne was interested in the impact of geology on the distribution of species and plant communities, and described the site (Carne 1910): *The present note deals with an interesting, though small, patch of vegetation occurring on an outcrop of a limestone at Grose Vale, Hawkesbury District. The deposit is to be found below Box Hill, and is followed by the Horseshoe Bend Road, which, running N.E. and S.W., joins the main Kurrajong and Grose Vale Roads. It is on the eastern slope of the hill, which curves to form a natural amphitheatre sheltering orchards and other cultivated areas. At about 100 yards from the Grose Vale end, and following the road for about half a mile, nearly to what is known as Lookout Hill, is the outcrop, with its vegetation, which is so distinct as to be noticeable against the hillside from several miles away. Another small deposit, denuded of timber, occurs near the church, about half a mile from Kurrajong Road. The deposit is about 800 feet above sea-level, and about 8 miles by road from Richmond. The dense growth of trees, entangled with many creepers, and the absence of Eucalypts, resembles that of the luxuriant gully– brushes of the eastern slopes of Kurrajong Range; or, perhaps, more nearly, those on volcanic soils, such as at Mountain Lagoon, Mount Wilson, or even of the Illawarra slopes. Above the road, this vegetation extends nowhere more than 20 yards, while, on the steep slope below, its width has been much greater, probably owing to the soil having been washed down from the outcrop.*

The site is now more or less located between Grose Vale Road and Westbury Road, Grose Vale (lat 33° 34' S; long 150° 38' E, c. 230 m elevation).

The botanist's published word is often able to survive the years better than native vegetation, and botanical interest can be passed down to succeeding generations. Carne's paper was picked up by Bill May who visited the site in 1984 and recorded the species present there at that time.

In 1996 as part of the National Parks and Wildlife Service Urban Bushland Biodiversity Survey (James 1997), Anders Bofeldt, a rainforest and rare species expert made some herbarium collections from Grose Vale. A summary list in the UBBS (Volume 2) is based on James' and Bofeldt's records – These records were from the steep slopes and a narrow zone on the lower side of Grose Vale Road (T. James pers. comm. 2011). In 2009 a list was made by Peter Lister (with Steve Clarke) who visited the site (see Figures 1, 2) as research for his biography of WM Carne (Lister 2009), and recorded species accessible from the road. Local resident Robin Woods has also prepared a list for the area based on recollection and observations (R.Woods pers. comm. Nov 2011), as part of a submission on listing Western Sydney Dry Rainforest (WSDRF) as an endangered ecological community under the Commonwealth Environment Protection and Biodiversity Conservation (EPBC) Act 1999 .

Species lists often remain unpublished and inaccessible, but Bill May's 1984 list and the original 1910 list, were published in Benson (1992) as Table 8. Unfortunately I incorrectly and inadvertently cited Joseph E Carne's (WM Carne's father) 1908 paper on the Western coalfields as the source of the 1910 list; I take this opportunity to apologise for misleading

**Table 1 Some interesting Sydney area botanical sites with sequences of historical botanical data (references grouped broadly as 19th or 20th century) and any recent updates and current status.**

EEC= Endangered Ecological Community; NR= Nature Reserve; NP= National Park, SCA= State Conservation Area

| | **Pre-1900** | **1901-2000** | **Recent updates** | **Current status** |
|---|---|---|---|---|
| Umina sand ridges | | Soil–vegetation studies<br>Burgess & Drover 1952 | Payne et al. 2010 | EEC, private |
| Mt Wilson- Mount Tomah basalt caps | 1820s description by A.Cunningham; specimens Jesse Gregson | Brough etal 1924; McLuckie & Petrie 1926; Petrie 1925; specimens Keith Ingram | | Part NP |
| Grose Vale *limestone* | | Species list and descrip. Carne 1910; Benson 1992 | This paper | EEC, private |
| Agnes Banks sand deposit | | Maze 1942, Simonett 1950, Benson 1981 | | Part NR, |
| Bents Basin | 19th C specimens G. Caley, JH Maiden | Specimens JH Maiden, LAS Johnson; Benson et al. 1990 | | NR, SCA |
| Kurnell-Meeting place | 1770 specimens, description Banks & Solander | Specimens JH Maiden | Benson & Eldershaw 2007 | Part NP |
| *Native Vineyard* at Cobbitty | 1867 spp list and descrip. Woolls 1867 | Benson 1992 | | EEC, private |
| Bulli escarpment | 1820s descrip. A Cunningham | 1930s ecological descrip. Davis 1936, 1941a,b | | Part NP, SCA |
| Five Islands, Illawarra | | Davis et al 1938, Mills 1990 | | NR |

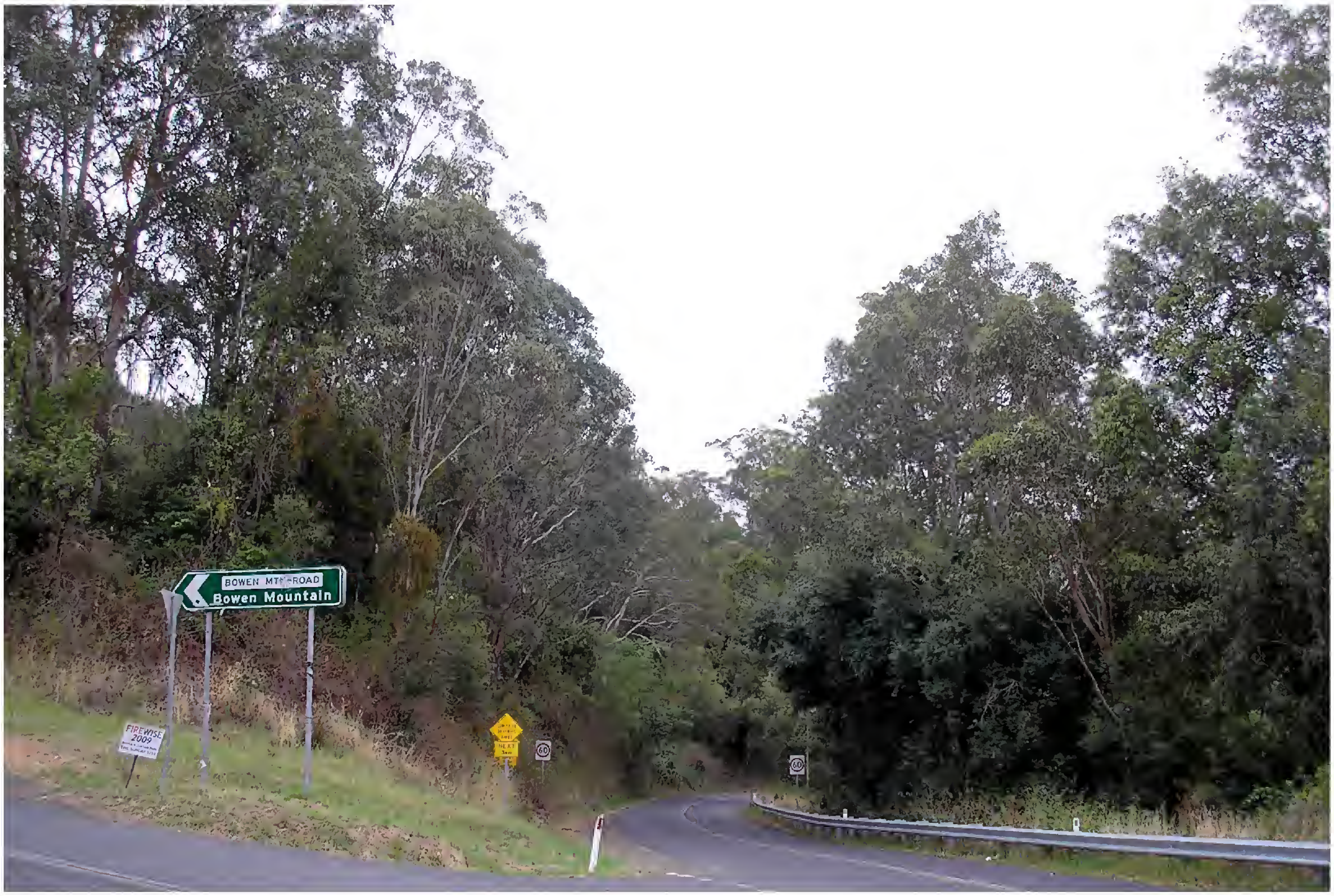

**Fig. 1.** Junction of Bowen Mountain and Grose Vale Roads in 2009 showing roadside vegetation remnants. (photo Peter Lister)

readers. JE Carne's (1908) paper is itself interesting for its descriptions of the vegetation of some of the volcanic necks and caps in the western Blue Mountains, and in passing indicates the considerable rural activity at that time in an area that is now regarded as largely natural. His name has been applied to Carne Creek, an upper tributary of the Wolgan River with a series of botanically important Newnes Plateau Shrub Swamps. The contributions to NSW botany of both Carnes, father and son, were recognised in the naming of *Acacia carneorum* (= 'of the Carnes') by Joseph Maiden.

WM Carne's Grose Vale specimens remained at Hawkesbury Agricultural College in the Musson Herbarium until they were transferred to the National Herbarium of NSW in 1979, and after being databased during the last decade, became available for study. I have revisited the lists compiled in 1910 for updated naming, and though there are no specimens to accompany the 1984 and 2009 lists, there are other collections from recent times (mainly Anders Bofeldt's 1996 collections) to confirm botanical identity (Appendix 1). Of Carne's published lists we can confirm that of the 36 species listed for the limestone outcrop, 78% have supporting specimens; of the 11 intermediate habitat species, 55% have specimens; and of the 67 shale soil species, 51% have specimens (Table 2).

In 1910 Carne expressed concern that the pace of clearing and weed invasion was clearly going to destroy the interesting vegetation: *There is no doubt that, even up to recent years, this flora covered an area much larger than it does to-day. Many roadside plants, both native and introduced, have established themselves. Clearing is still going on. The conditions for luxuriant growth are no longer so favourable, and in a few years this interesting, patch of vegetation will probably disappear.* Similar fears are expressed for many sites today. Carne's response was to record the site by collecting specimens and describing it in the scientific media.

Whether Carne's work provided any protection in the early part of the 20th century is unknown, but drawing attention to the peculiarities of the local site has led to botanical responses in the last couple of decades, and some limited on-ground habitat rehabilitation. Robin Woods (pers. comm. Nov 2011) suspects that Carne only had access to roadside sites and never knew about some species. She found for example, some of the biggest and oldest *Croton insularis* with very diverse understorey in one property further west of the site,

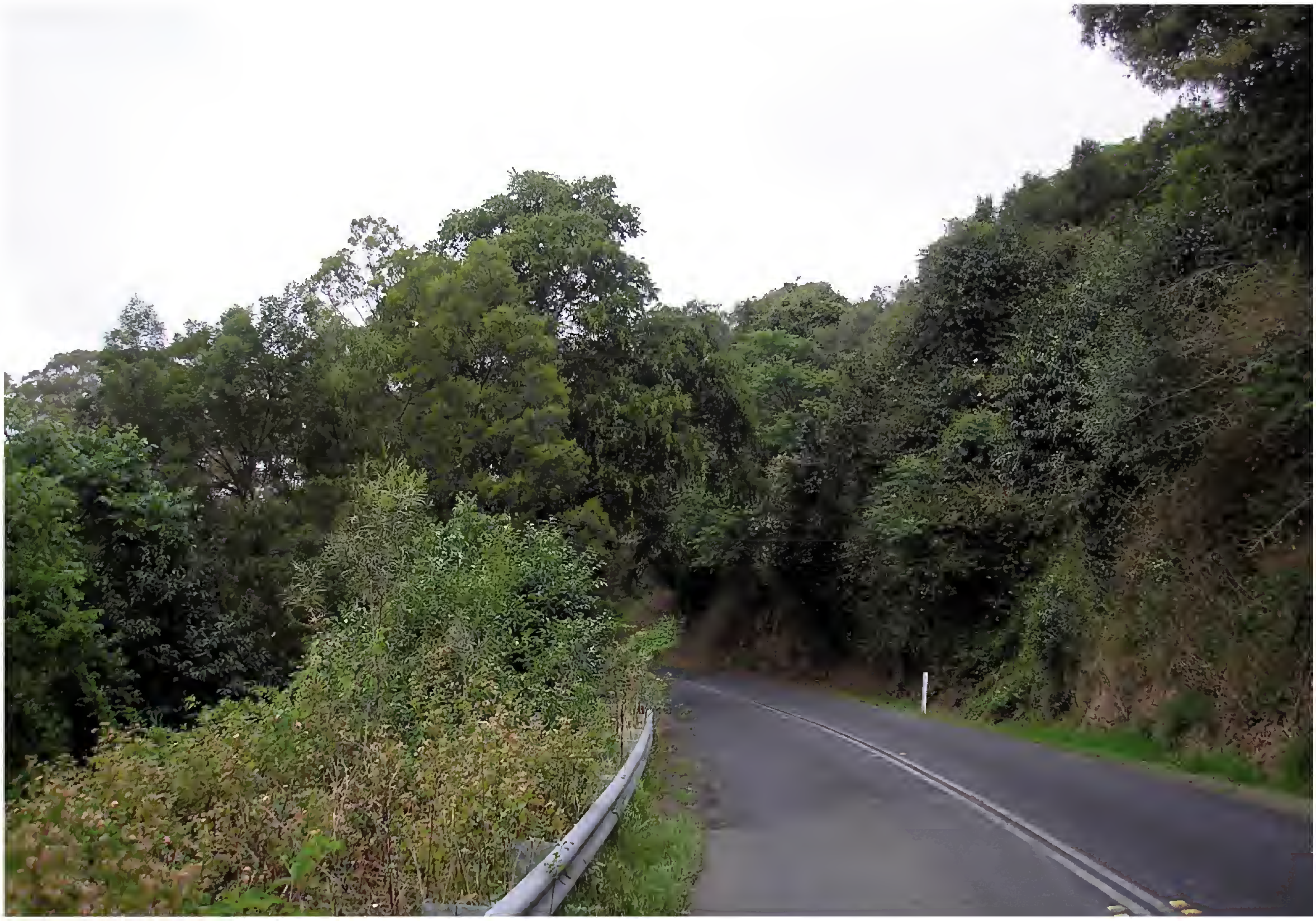

**Fig. 2.** Grose Vale site in 2009 showing rainforest remnants along roadside. (photo Peter Lister)

**Table 2 Specimen confirmation of Carne's 1910 Grose Vale list. Soil categories follow Carne (1910).**

| | Limestone | intermediate | Shale |
|---|---|---|---|
| Carne's 1910 list | 36 | 11 | 67 |
| Carne specimens | 28 | 6 | 34 |
| Incorrect taxa | 4 | | |
| Confirmed by later specimen or listing | 4 | | |
| Percentage of Carne's list with confirmed specimen | 78% | 55% | 51% |

**Table 3 Number of species recorded in surveys at Grose Vale (1910, 1984, 1996, 2009, 2011) and percentage of flora surviving (2009-2011). Only limited collections were made in 1996.**

| | Limestone soil | intermediate soil | Shale soil |
|---|---|---|---|
| 1910 | 32 plus 4 incorrect taxa | 11 | 67 |
| 1984 | 18 | 10 | 23 |
| 1996 | 9 | 2 | 3 |
| 2009 | 19 | 5 | 16 |
| 2011 | 23 plus 5 possibles | 10 | 34 |
| 2009, 2011 combined | 24 plus 5 possibles | 10 | 36 |
| Percentage of 1910 flora surviving | 75% | 91% | 54% |

which resulted in $20 000 in funding for regeneration from the NSW Dept of Environment & Conservation.

Today, while the patch is much reduced in area, it is still possible to see many of the species recorded by Carne 100 years ago. Comparisons with the historic data (Table 3) confirm that a significant part of the flora is still present in the site area: 75% of the listed limestone flora (2009 and 2011 combined), and 91% and 54% of the intermediate and shale flora respectively. These last two statistics are artificially low as searches have targeted the unusual limestone flora. The shale flora is more widespread in the area. The site is freehold land and as far as is known there is no particular protection for this site at local government level. It is likely that the relative steepness of the site, and its situation at the junction of several roads, may all have helped survival, but the persistent nature and longevity of many native plant species has also been important. The resilience of many native species in response to adverse conditions was not recognised in 1910, though there are limits particularly in the face of the extensive shading from the exotic woody weed African Olive, *Olea europaea* subsp. *cuspidata*, that has developed over the last two decades. At Cobbitty where *Olea* was well established in the 1970s its severe competition had already lead to loss of natives by 1990.

At Grose Vale some form of formal protection (on nearby properties goats appear to be underscrubbing the forests), as well as further careful recording, a management plan, and weed control, are needed now if this important vegetation remnant is to survive beyond 2110.

## Discussion

Can this attractiveness of particular sites to botanists and fellow scientists be used to advantage? Repeated visitation and supporting documentation is an important way to gather scientific information on changes longer than lifespans of individual researchers. Most of our primary 18th and 19th century historical botanical information is limited to plant specimens, generally with very little in the way of annotation except for locality data. There are very few descriptions of the native vegetation for specific sites; the few descriptions that exist are therefore important and especially so when the actual sites still remain. A list of such sites in western Sydney is small, probably restricted to the Native Vineyard at Cobbitty, Grose Vale limestone, Bents Basin, the Agnes Banks sand deposit and possibly Nortons Basin. But there may still be historical data to be found in unpublished letters, diaries or journals. For example it would be exciting to find a 19th century list of native plants from Prospect Hill, Parramatta Park, Penrith Weir, Yarramundi, or somewhere on the Georges River.

Where historically-documented sites exist, they need to be protected in local legislation and if private land, then should at least be accessible to scientific study, although not necessarily open to the public. Where conservation zoning is appropriate some funding could be provided. Interestingly both the Native Vineyard and Grose Vale limestone sites are part of the Western Sydney Dry Rainforest Endangered Ecological Community (WSDRF), now listed under the NSW *Threatened Species Conservation* (TSC) Act, and proposed for listing under the Commonwealth *EPBC* Act.

There are no similarly historically-documented sites in the adjacent and more extensive Cumberland Plain woodland vegetation, presumably because its vegetation appeared commonplace and widespread in the 19th century landscape. However much of the vegetation of the Cumberland Plain and greater Sydney area has been subject to major clearing and disturbance over the past 200 years, and almost all vegetation (apart from that growing on the low-fertility sandstones) is recovering in some way from past disturbance. The degree of disturbance seems to be somewhat discounted in much of our thinking however, perhaps because none of us have seen an undisturbed example. This is important. In the absence of the 1867 list for the Native Vineyard at Cobbitty it would be impossible to believe such a site existed, so unexpected is the composition of the flora and its particular location. The uniqueness of the site was evidently special enough to draw Woolls' attention to it at a time when one would expect that there were still many other equally anomalous sites surviving. His documentation provided an impetus for revisiting the site and now provides a knowledge base for its future rehabilitation. Documentation in 1937 drew subsequent attention to the sand deposit at Agnes Banks, and ultimately to some vegetation being protected as Agnes Banks Nature Reserve in 1982, though without survival of this remnant it would be similarly hard to believe that such a site existed amongst the grassy woodland of western Sydney. A smaller sand deposit was once reported at Wilberforce (Maze 1942) and I remember seeing some remnant Banksias there in the 1970s, but sandmining had by then almost obliterated all physical evidence, and the literature record was very scant. Better recording and specimen collection would at least have provided an idea of its extent, and possibly provided a basis for future restoration. This was done for a remnant at Elderslie, which is now listed as Elderslie Banksia Scrub Forest Endangered Ecological Community under the TSC Act.

This history of disturbance is likely to have had differential impact on different flora species, (for example stringybarks may have been preferentially selected for timber above other species such as ironbarks, resulting in an artificial change in relative dominance Jon Sanders, pers. comm. 2012). This disturbance also means that the vegetation is very much still changing – e.g. areas that we see and accept as woodland may gradually transform into forest as trees regenerate and mature to sizes that we do not currently see. As a result of these changes, 'new' species may turn up in unexpected places as recovery occurs. It is also the case that there is increasing demand for the regeneration and even restoration of the native vegetation communities, a demand that we should be meeting and encouraging. Checking of historic botanical records, and revisiting these 'historic' sites may provide important information and reference points to aid restoration, such as which species have 'gone missing' at other sites, or are at unnaturally low abundance as a result of disturbance.

In my experience those involved in plant recording are almost invariably driven by a passion for finding or refinding plant species (this applies to those I have acknowledged below). For example Anders Bofeldt's passion for revisiting old botanical sites led to his re-discovery of the rare rainforest vine *Cynanchum elegans*, (then thought to be extinct in the Sydney region) at sites in western Sydney and the Illawarra, an action that has helped ensure that this species survives in western Sydney and the Illawarra.

### *Ongoing change and repeated recording*

Long term monitoring plots at the Australian Botanic Garden, Mount Annan (Benson & Howell 2002), and work elsewhere (e.g.Watson et al. 2009) demonstrate that the flora species visible at sites in western Sydney may change quite markedly from time to time, with many species being either relatively short term or occasional in their presence (e.g. after fire, following rains etc). Whilst it would be expected that this temporal change would be less marked at a dry rainforest site, it is unlikely that all the flora will be seen on one visit. Repeated visits are therefore valuable in terms of getting a complete picture of the flora, and repeated visits by the same botanist over the shorter term (e.g. within a few years) may therefore also be valuable. Visits can be timed to sample under different climatic or environmental conditions; the important factor here is to record at each visit, allowing real comparison of information to detect any change.

To conclude, there is value in documenting sites, and continuing this over many years. Though we have only limited records from the 19th and 20th centuries, what we do have provides critical evidence for our view of the ecological world at that time, and an important time-frame for understanding the rate of subsequent changes. We cannot revisit the 19th or 20th century landscapes, but we can enhance the value of existing sites by beginning their documentation now.

## Acknowledgements

Peter Lister's work on WM Carne provided the initial spark for this paper, and together with Steve Clarke of the University of Western Sydney Richmond campus provided photos and species lists. Robin Woods and Teresa James generously provided species lists and supporting information. Jonathan Sanders raised interesting points for discussion, as always. The collections made by the late Anders Bofeldt, who passed away unexpectedly in 2011, are acknowledged.

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Manuscript accepted 23 May 2012

## Appendix 1

## Species listed for Grose Vale compiled by Carne in 1910 for his limestone, intermediate and shale substrates, with subsequent occurrence noted by later recorders, either from their lists or specimen collections.

Additional species not originally noted by Carne have generally not been included, as the exact locations of records are not known. Plant names follow PlantNet.

| **Family** | **Species** | **Carne 1910 list** | **Carne 1910 species** | **Bill May 1984 list** | **Bofeldt 1996 species** | **Lister & Clarke 2009 list** | **Robin Woods 2011 list** |
|---|---|---|---|---|---|---|---|
| **LIMESTONE SOIL** | | | | | | | |
| Myrtaceae | *Acmena smithii* | limest. | 1910 | | | 2009 | 2011 |
| Adiantaceae | *Adiantum formosum* | limest. | 1910 | | | 2009 | 2011 |
| Adiantaceae | *Adiantum silvaticum* | limest. | | | | 2009 | 2011 |
| Sapindaceae | *Alectryon subcinereus* | limest. | 1910 | 1984 | | 2009 | 2011 |
| Rhamnaceae | *Alphitonia excelsa* | limest. | 1910 | 1984 | | 2009 | 2011 |
| Celastraceae | *Elaeodendron australis* | limest. | 1910 | 1984 | | 2009 | 2011 |
| Vitaceae | *Cayratia clematidea* | limest. | 1910 | 1984 | | | 2011 |
| Poaceae | *Cenchrus caliculatus* | limest. | 1910 | | | | |
| Vitaceae | *Cissus antarctica* | limest. | 1910 | 1984 | | 2009 | 2011 |
| Vitaceae | *Cissus hypoglauca* | limest. | 1910 | 1984 | | 2009 | 2011 |

| **Family** | **Species** | **Carne 1910 list** | **Carne 1910 species** | **Bill May 1984 list** | **Bofeldt 1996 species** | **Lister & Clarke 2009 list** | **Robin Woods 2011 list** |
|---|---|---|---|---|---|---|---|
| Ebenaceae | *Diospyros australis* | limest. | 1910 | | 1996 | | possible |
| Blechnaceae | *Doodia aspera* | limest. | 1910 | | | | 2011 |
| Boraginaceae | *Ehretia acuminata* var. *acuminata* | limest. | 1910 | 1984 | | | 2011 |
| Eupomatiaceae | *Eupomatia laurina* | limest. | 1910 | | | | possible |
| Moraceae | *Ficus coronata* | limest. | 1910 | 1984 | | | 2011 |
| Sapindaceae | *Guioa semiglauca* | limest. | 1910 | 1984 | | 2009 | 2011 |
| Malvaceae | *Hibiscus heterophyllus* | limest. | 1910 | 1984 | | 2009 | 2011 |
| Pittosporaceae | *Hymenosporum flavum* | limest. | 1910 | 1984 | 1996 | 2009 | 2011 |
| Menispermaceae | *Legnephora moorei* | limest. | 1910 | 1984 | | 2009 | 2011 |
| Apocynaceae | *Marsdenia rostrata* | limest. | 1910 | 1984 | | | |
| Meliaceae | *Melia azedarach* | limest. | 1910 | 1984 | | 2009 | 2011 |
| Lauraceae | *Neolitsea dealbata* | limest. | | | | | possible |
| Passifloraceae | *Passiflora herbertiana* | limest. | | 1984 | | 2009 | 2011 |
| Pteridaceae | *Pellaea falcata* | limest. | | | | 2009 | 2011 |
| Pittosporaceae | *Pittosporum multiflorum* | limest. | 1910 | 1984 | | | 2011 |
| Myrtaceae | *Rhodamnia rubescens* | limest. | 1910 | 1984 | | 2009 | 2011 |
| Rosaceae | *Rubus moluccanus* var. *trilobus* | limest. | 1910 | | | | possible |
| Santalaceae | *Santalum obtusifolium* | limest. | 1910 | | 1996 | | possible |
| Rutaceae | *Sarcomelicope simplicifolia* | limest. | 1910 | | 1996 | 2009 | |
| Menispermaceae | *Sarcopetalum harveyanum* | limest. | 1910 | 1984 | | 2009 | 2011 |
| Winteraceae | *Tasmannia insipida* | limest. | 1910 | | | | |
| Meliaceae | *Toona ciliata* | limest. | 1910 | 1984 | 1996 | 2009 | 2011 |
| **NO HERB RECORDS FOR Grose Vale** | | | | | | | |
| Rousseaceae | *Cuttsia viburnea* No, only NC North from Landsdowne R | limest. | | | | | |
| Lauraceae | *Endiandra* | limest. | | | | | |
| Iridaceae | *Libertia paniculata* | limest. | | | | | possible |
| Adoxaceae | *Sambucus australasica* | limest. | | | | | |
| **ADDITIONAL SPECIES NOT ORIGINALLY LISTED** | | | | | | | |
| Euphorbiaceae | *Croton insularis* | | | 1984 | 1996 | | 2011 |
| Lauraceae | *Cryptocarya microneura* | | | | 1996 | | |
| Moraceae | *Maclura cochinchinensis* | | 1910 | 1984 | | | 2011 |
| Apocynaceae | *Marsdenia flavescens* | | | | 1996 | | |
| **INTERMEDIATE SOIL** | | | | | | | |
| Aphanopetalaceae | *Aphanopetalum resinosum* | interm. | | 1984 | | | |
| Sterculiaceae | *Brachychiton populneus* | interm. | 1910 | 1984 | | 2009 | 2011 |
| Adoxaceae | *Breynia oblongifolia* | interm. | | 1984 | | | 2011 |
| Lamiaceae | *Clerodendrum tomentosum* | interm. | | 1984 | | 2009 | 2011 |
| Euphorbiaceae | *Croton verrauxii* | interm. | | 1984 | 1996 | | 2011 |
| Phyllanthaceae | *Glochidion ferdinandi* var *ferdinandi* | interm. | | 1984 | | 2009 | 2011 |
| Rutaceae | *Melicope micrococca (=Euodia)* | interm. | 1910 | 1984 | 1996 | | 2011 |

| Family | Species | Carne 1910 list | Carne 1910 species | Bill May 1984 list | Bofeldt 1996 species | Lister & Clarke 2009 list | Robin Woods 2011 list |
|---|---|---|---|---|---|---|---|
| Bignoniaceae | *Pandorea pandorana* | interm. | 1910 | 1984 | | 2009 | 2011 |
| Phyllanthaceae | *Phyllanthus gunnii (=gasstroemii)* | interm. | 1910 | | | 2009 | 2011 |
| Myrsinaceae | *Myrsine variabilis* | interm. | 1910 | 1984 | | | 2011 |
| Ulmaceae | *Trema tomentosa* var. *aspera* | interm. | 1910 | 1984 | | | 2011 |
| **SHALE SOIL** | | | | | | | |
| Malvaceae | *Abutilon oxycarpum* | shale | 1910 | 1984 | 1996 | | |
| Fabaceae | *Acacia parramattensis (=A. decurrens)* | shale | | 1984 | | 2009 | 2011 |
| Fabaceae | *Acacia longifolia* | shale | | 1984 | | | |
| Rosaceae | *Acaena novae-zelandiae* | shale | 1910 | | | | |
| Rosaceae | *Acaena ovina* | shale | | | | | |
| Poaceae | *Aristida vagans* | shale | | | | | |
| Poaceae | *? Austrostipa rudis* | shale | | | | | |
| Poaceae | *Austrodanthona pilosa* | shale | | | | | |
| Poaceae | *Bothriochoa decipiens* | shale | | | | | |
| Pittosporaceae | *Bursaria spinosa* | shale | 1910 | 1984 | | 2009 | 2011 |
| Myrtaceae | *Callistemon salignus* | shale | | 1984 | | | 2011 |
| Asteraceae | *Calotis lappulacea* | shale | 1910 | | | | |
| Cyperaceae | *Carex appressa* | shale | 1910 | | | | |
| Cyperaceae | *Carex longebrachiata* | shale | 1910 | | | | 2011 |
| Ranunculaceae | *Clematis aristata* | shale | 1910 | | | 2009 | 2011 |
| Ranunculaceae | *Clematis glycinoides* | shale | 1910 | | | 2009? | |
| Commelinaceae | *Commelina cyanea* | shale | | | | 2009 | 2011 |
| Poaceae | *Cymbopogon refractus* | shale | | | | | |
| Apiaceae | *Daucus glochidiatus* | shale | | | | | |
| Fabaceae | *Desmodium brachypodum* | shale | 1910 | | | | |
| Phormiaceae | *Dianella longifolia* var. *longifolia* | shale | 1910 | 1984 | | | |
| Poaceae | *Dichantheum sericeum* | shale | | | | | |
| Poaceae | *Dichelachne sciurea* | shale | | | | | |
| Convolvulaceae | *Dichondra repens* | shale | | | | | 2011 |
| Sapindaceae | *Dodonaea viscosa* | shale | 1910 | 1984 | | | 2011 |
| Poaceae | *Echinopogon ovatus* | shale | | | | | 2011 |
| Chenopodiaceae | *Einadia trigonos* | shale | | 1984 | | | |
| Onagraceae | *Epilobium billardierianum* | shale | | | | | |
| Poaceae | *Eragrostis leptostachya* | shale | | | | | |
| Myoporaceae | *Eremophila debilis* | shale | 1910 | | | | |
| Myrtaceae | *Eucalyptus moluccana* | shale | | 1984 | | 2009 | 2011 |
| Myrtaceae | *Eucalyptus tereticornis* | shale | | 1984 | | | 2011 |
| Luzuriagaceae | *Eustrephus latifolius* | shale | 1910 | 1984 | | 2009 | 2011 |
| Santalaceae | *Exocarpos cupressifomis* | shale | 1910 | | | | |
| Cyperaceae | *Gahnia aspera* | shale | 1910 | | | | 2011 |
| Cyperaceae | *Gahnia melanocarpa* | shale | 1910 | | | | |
| Luzuriagaceae | *Geitonoplesium cymosum* | shale | | 1984 | | | 2011 |

| **Family** | **Species** | **Carne 1910 list** | **Carne 1910 species** | **Bill May 1984 list** | **Bofeldt 1996 species** | **Lister & Clarke 2009 list** | **Robin Woods 2011 list** |
|---|---|---|---|---|---|---|---|
| Geraniaceae | *Geranium solanderi* | shale | | 1984 | | 2009 | |
| Fabaceae | *Glycine cIandestina* | shale | 1910 | 1984 | | 2009 | 2011 |
| Fabaceae | *Indigofera australis* | shale | 1910 | 1984 | | 2009 | 2011 |
| Juncaceae | *Juncus usitatus* | shale | 1910 | | | 2009 | 2011 |
| Poaceae | *Leptochloa decipiens* | shale | | | | | |
| Ericaceae | *Leucopogon juniperinus* | shale | 1910 | 1984 | | | 2011 |
| Lomandraceae | *Lomandra longifolia* | shale | | | | | 2011 |
| Myrtaceae | *Melaleuca styphelioides* | shale | | 1984 | | 2009 | 2011 |
| Lamiaceae | *Mentha diemenica* (as *saturioides*) | shale | 1910 | | | | |
| Poaceae | *Microlaena stipoides* | shale | | | | | 2011 |
| Solanaceae | *Nicotiana forsteri* | shale | 1910 | | | | |
| Oleaceae | *Notelaea longifolia* | shale | | | | 2009 | 2011 |
| Amaranthaceae | *Nyssanthes diffusa* (as *erecta*) | shale | 1910 | | 1996 | | 2011 |
| Poaceae | *Oplismenus imbecillis* | shale | | | | 2009 | 2011 |
| Asteraceae | *Ozothamnus diosmifolius* | shale | | | | | 2011 |
| Poaceae | *Panicum pygmaeum* | shale | 1910 | | 1996 | | |
| Plantaginaceae | *Plantago debilis* | shale | | | | | 2011 |
| Lamiaceae | *Plectranthus parviflorus* | shale | 1910 | 1984 | | 2009 | 2011 |
| Lobeliaceae | *Pratia purpurascens* | shale | 1910 | | | | 2011 |
| Acanthaceae | *Pseuderanthemum variabile* | shale | 1910 | 1984 | | | 2011 |
| Rosaceae | *Rubus parvifolius* | shale | 1910 | 1984 | | | 2011 |
| Polygonaceae | *Rumex brownii* | shale | | | | | |
| Asteraceae | *Senecio glomeratus* | shale | | | | | |
| Asteraceae | *Sigesbeckia orientalis* | shale | 1912 | | | 2009 | 2011 |
| Smilacaceae | *Smilax australis* | shale | | 1984 | | | |
| Solanaceae | *Solanum prinophyllum* | shale | 1910 | | | | 2011 |
| Solanaceae | *Solanum stelligerum* | shale | 1910 | 1984 | | | 2011 |
| Urticaceae | *Urtica incisa* | shale | 1910 | | | | 2011 |
| Asteraceae | *Vittadinia tenuissima* | shale | 1910 | | | | |
| Campanulaceae | *Wahlenbergia gracilis* | shale | | 1984 | | | 2011 |